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13. ABSTRACT *(Maximum 200*

The risk of low-back disorders (LBD) may be particularly great for women in the military, influencing training effectiveness, costs, and military readiness. The goal of this research is to quantify musculoskeletal loads on the spine of women performing military manual materials handling (MMH) tasks. This will permit assessment of LBD risk factors for military women, and the potential to evaluate tasks and training methods for female military personnel.

Our efforts are progressing in general accordance with the proposal and timeline. Magnetic Resonance Images (MRI) have been employed to measure the muscle cross-sectional areas, lateral and sagittal moment arms distances, and muscle vector angles in both healthy men and women. Muscle force-velocity and length strength relationships have been determined with biomechanical model performances determined, with a few more subjects needed to be collected to solidify the promising results. Finally, the validation of the biomechanical model using the relationships determined from muscle geometry and force-velocity and length-strength relationships is currently in progress.

After the second year of this research effort, we are progressing well and are confident that an accurate biomechanical model can be developed for the evaluation of spinal loading of women performing military MMH tasks.

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William S. Munn 10/23/96

PI - Signature Date

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EXECUTIVE SUMMARY

Low back injuries in female military personnel can significantly impact training effectiveness, costs and military readiness. Low back injuries accounted for 75% of compensable military injuries in 1988 through 1991 (Army Safety Center, 1992). When one considers that women have significantly higher incidence of lost time injuries during basic training than men (Jones et al., 1988), it is apparent that the risk of work related low back disorders (LBD) may be particularly great for women in the military. Heavy manual materials handling (MMH) that would challenge the injury tolerance of most industrial workers' spines has been shown to be the most physically demanding task in 90% of all military job specialties (Sharp and Vogel, 1992). As these military occupational specialties (MOSs) are becoming increasingly available to women, the risk of LBD to women will have greater consequences as they fill these roles, particularly when considering a downsizing military. Thus, there is a need to reliably assess the risk of military task related LBD to women, and to identify potential features or training that might mitigate that risk.

The goal of this research is to extend the capability of predicting musculoskeletal loads on the trunk and spine to women performing realistic MMH tasks. Current models of musculoskeletal loading on the spine are based upon male biomechanics, and must be enhanced to account for the anatomical geometry and physiology of the female musculoskeletal torso. This will permit accurate evaluation of the spinal loads in women as they perform military MMH activities, and the potential to assess the relative risk of female military personnel performing MMH tasks in comparison to male personnel.

The first part of this effort is complete, whereas the second part is near completion, and the third part has begun. The first part consisted of employing Magnetic Resonance Imaging (MRI) techniques to quantitatively describe the internal geometry of the female trunk musculoskeletal system so that the model can accurately represent internal trunk mechanics. The second part consists of the evaluation of the muscle force-velocity and length-strength relationships that are unique to the female trunk musculature and physiology, which is currently in progress. Part three, which is in its initial stages,

will validate the contributions of the internal geometric relationships and the length-strength and force-velocity relationships into a female specific biomechanical model.

Our efforts in this research is progressing in accordance with the proposed timeline as we expected. To date, we have collected and analyzed all the imaging data on healthy women. We have managed to expand this phase of the research, to allow assessment of healthy subjects for improved validity and to collect data of healthy males for direct comparison. The results agree with existing literature, indicating the methods, data, and processing we have been using will lead to valid mechanical representations of the torso. The determination of the female length-strength and force-velocity muscle relationships have progressed to a point where most of the subjects have been collected, and stable and promising results have been obtained. The additional subjects needed to be collected will serve to enhance promising results to date. The data collection for Part 3 has begun, with both males and females being subjected to asymmetric and sagittally symmetric lifting exertions to validate the biomechanical model developed using the data and relationships found in Part1 and Part 2.

After the second year of this research effort, we remain confident that we will successfully develop an accurate biomechanical model for the evaluation of spinal load of women performing MMH tasks. These results may permit assessment of work related LBD, and identification of methods and training techniques that will reduce the risk of low back injury in female military personnel.

PART 1: Anthropometric MRI Measurement of Female Musculoskeletal Torso

Introduction

The control of women's low-back disorder (LBD) risk should be a priority for the military to mitigate escalating injuries and associated costs, and to maintain military readiness and combat effectiveness. Low back injuries accounted for 75% of compensable military injuries and have cost the Army between 46.9 and 61 million dollars per year from 1988 through 1991 (Army Safety Center, 1992). When one considers that women have significantly higher incidence of lost time injuries during basic training than men (Jones et al., 1988), it is apparent that the risk of work related LBD may be particularly great for women in the military. The cost of LBD risk among military women extends beyond medical care expenditures and long term or permanent compensation for the soldier. There is a great cost associated with lost duty time, training and retraining replacement personnel if a soldier must be discharged because of a LBD. Furthermore, military effectiveness and readiness are compromised if the soldier is not able to perform peacetime or combat related tasks because of a LBD.

Many of the military occupational specialties (MOSs) have recently been made available to military women (Army Times, 1994). As of 1995 there were women filling roles as combat engineers, in field artillery, and land combat MOSs. The number of women in these combat related MOSs is expected to increase. As women fill an expanded role in the modern military, the risk of lost female personnel due to LBD will have greater consequences upon military readiness and combat effectiveness than ever before. With military downsizing, the importance of each military women, and the repercussions of LBD will become critical.

Many of the MOSs now being filled by women requires heavy manual material handling and would be expected to challenge the tolerance of most industrial workers' spines. Sharp and Vogel (1992) have shown that "heavy MMH is the most physically demanding task in 90% of all military job specialties." Yet these activities have never been quantitatively evaluated with military women. Thus, there is a need for a biomechanical model that can accurately and reliably assess and evaluate the risk of LBD to women as well as what features or training might mitigate that risk.

The Ohio State University EMG-assisted biomechanical model can be developed to provide a tool to assess and evaluate the risk of LBD to women performing military MMH tasks as part of their MOSs. Our previous efforts have demonstrated that we have been able to build a three-dimensional model of the trunk that is capable of accurately assessing spine loads during free-dynamic trunk motion which accounts for muscle co-contraction (Granata and Marras, 1993; Marras and Granata, 1995; Marras and Sommerich, 1991a,b). However, the modeling efforts to date have been successful in modeling the trunk geometry and subsequent loading imposed upon the spine of only males performing manual materials handling activities.

The geometry of the female trunk is vastly different from that of the male. Women tend to possess greater hip breadth and narrower abdominal depth than men (Pheasant, 1988). The sacroiliac joint is positioned several centimeters anteriorly in the female changing the moment arm associated with the external load as well as affecting the internal moment arm distances between the muscles and the point of rotation of the spine (Tischauer, 1978). In addition, it is suspected that the muscle attachment locations are significantly different between males and females. These changes will dramatically affect the force-length and force-velocity relationships that are vital for the determination of muscle force. In addition, one must understand the differences in the muscle lines of action (attachments) so that the trunk mechanics representation accurately reflects loading of the female trunk.

The ultimate goal of this research is to extend the capability of predicting musculoskeletal loads to that of women performing realistic MMH tasks. This model will be employed to assess the relative risk for musculoskeletal injury due to a MMH task for women relative to men, and to evaluate the proposed changes to those tasks to quantify the change in LBD risk. This EMG-driven biomechanical model will then be available as a tool to assess the risk associated with specific MMH tasks performed as part of MOSs that have recently been made available to military women. In this manner it will be possible to: a) assess risk for a given task, b) evaluate the physical attributes of a potential recruit that would place her at an increased risk of LBD, and c) determine how training or workplace procedures might be changed to minimize risk of LBDs to women (and men) performing the military MMH task.

In order to accomplish these objectives, it will be necessary to accomplish five specific aims. 1.) Quantitatively describe the internal geometry of the female trunk musculoskeletal system so that the model can accurately represent internal trunk mechanics and lines of muscle action. Magnetic Resonance Imaging (MRI) will be used to collect this information in a safe and accurate manner. 2.) Determine the force-velocity relationship and length-strength relationships that are unique to the female trunk musculature. 3.) Implement female trunk geometry and muscle relationships into the existing OSU EMG-assisted biomechanical model. 4.) Test and validate the model under laboratory conditions. 5.) Use the model to evaluate military MMH tasks of physically demanding MOSs performed by both males and females.

Background and Objectives

The objective of Part 1 was to generate descriptive statistics to describe the relative anthropometric values of muscle cross-sectional areas, origins, and lines of action in the female torso. The EMG-assisted biomechanical currently accepts regression equations to predict muscle anthropometry of male subjects (Granata and Marras, 1993; Marras and Granata, 1995; Marras and Sommerich, 1991a,b). This is critical for scaling modeled muscle force amplitudes, dynamic behavior and to predict musculoskeletal loads. In order to generate accurate assessments of spinal loading and associated LBD risk of females performing military MMH tasks, it is necessary to generate a biomechanical geometry that accurately describes military age women. Although measures of soft tissue have been reported on elderly females (Chaffin et al., 1990; Kumar, 1988), there have been no studies designed to measure the trunk muscle area and geometry of young active women.

Administrative Note

In the accepted research proposal, the "Statement of Work Addendum" included the collection of anthropometric data describing relative trunk muscle sizes and biomechanical lines of action on 20 women from existing MRI scans. Thus, we were to find torso imaging data of women who had required medical diagnosis of disabilities. The originally proposed "Statement of Work" suggested MRI analyses be performed by scanning 20 healthy women. However, due to budget limitations imposed by USARMC prior to approving the research, it was necessary to revise this part of the research to meet the financial constraints with the "Statement of Work Addendum" as described above.

We have managed to supplement the experimental design of the MRI with alternative funding that will improve the validity and specificity of the research for the purposes of the research goals and objectives. This was achieved by finding the opportunity to support data collection of healthy military age women, a population which more realistically represents active military women. A local hospital with a state-of-the-art MRI facility has agreed to participate in this effort, allowing us the opportunity to scan 20 healthy women and 10 healthy men. This will improve the validity of the data by providing MRI scans of healthy women instead of scans from disabled women, avoiding confounding of musculoskeletal factors.

The alternative funding opportunity also allowed us to collect data for direct comparison of male versus female relative muscle areas, attachment points, and lines of action. To date, there have been no such published analyses of muscular mechanical geometry. This data will allow a direct comparison of the biomechanical loads generated by female versus male soldiers during MMH activities. The comparison will also permit a more valid assessment of LBD risk of women as compared to men, and the influence of task design upon gender related LBD risk.

Methods

Experimental Design

The subjects were placed in the MRI chamber at the Riverside Methodist Hospital, Columbus, OH, where cross-sectional images of the trunk were collected. A Philips GyroScan MRI was set to a spin echo sequence of TR=240 and TE=12, generating slices of 10 mm in thickness. Subjects were placed in a neutral position (supine postures with knees extended and hands lying across their abdomen) on the MRI gantry. The gantry moved the subjects into the center bore of the MRI magnet, aligning the subjects such that the scans could be performed on the desired region of the torso. A sagittal scout view was first collected to permit vertical quantification of individual transverse planes, and to ensure the cross-sectional scans would be captured in the field-of-view. A single set of 11 torso musculature scans was next performed, which were perpendicular to the gantry table at transverse levels through approximate centers of the vertebral bodies in the lumbar/sacrum and lower thoracic regions of the spine. Specifically, this included transverse scans of the torso through the T_8, T_9, T_{10}, T_{11}, T_{12}, L_1, L_2, L_3, L_4, L_5, and S_1 vertebral levels.

Subjects

Twenty females subjects of military age were recruited from the local community. In order to directly compare the female results with relative male anthropometry, MRI data were also collected on 10 male subjects of military age, also recruited from the local community. None of the subjects had a history of chronic activity limiting chronic back or leg injuries, nor were any experiencing any low back pain at the time of the MRI scan. Upon arrival, anthropometric data were collect from each subject including the age, height and weight, the trunk width and depth measured at the trochanter, iliac crest, and xyphoid process, trunk circumference about the iliac crest, and right and left trochanter height from the floor.

Data Extraction

The MRI scans for each subject were transferred onto a Philips GyroView, where muscle cross-sectional areas could be estimated, as well as muscle centroids located relative to the spinal vertebral body centroid (McGill et al., 1993). The GyroView allows the user to inscribe an object of interest with a computer mouse, which then provides descriptive statistical data including the area of the enclosed region and the three-dimensional location of the area centroids relative to the scan set origin. In this manner, each of the muscles of interest were identified, outlined, and quantified where present for each of the 11 scan levels. The quantified muscles included the right and left pairs of the erector spinae group, quadratus lumborum, latissimus dorsi, internal obliques, external obliques, rectus abdomini, and psoas major. The cross-sectional areas and centroids were also quantified for each vertebral body and the torso at each of the 11 scan levels. Vector component directions for each muscle from level to level were determined in both the lateral plane (*equation 1.2*) and the sagittal plane (*equation 1.3*).

$$\theta_{\mathrm{Lat}} = \frac{\Delta \mathbf{x}}{\Delta \mathbf{z}} \qquad (Eq\ 1.2)$$

$$\theta_{\mathrm{Sag}} = \frac{\Delta \mathbf{y}}{\Delta \mathbf{z}} \qquad (Eq\ 1.3)$$

where:

θ_{Sag} = Muscle vector angle in the sagittal plane from one vertebral level to the next;
θ_{Lat} = Muscle vector angle in the lateral plane from one vertebral level to the next;
Δx = Change in the muscle centroid lateral coordinate from one vertebral level to the next;
Δy = Change in the muscle centroid sagittal coordinate from one vertebral level to the next;
Δz = Change in the muscle centroid vertical coordinate from one vertebral level to the next.

To determine the muscle, vertebral body, and trunk cross-sectional areas and centroids at each scan level, each were inscribed several times, with the average of the observation used as the representative values. The coefficient of variation (C.V.) was calculated for the first 15 female subjects, which showed that using three observations re- ..ted in average C.V.'s of 9% or less for each muscle, with most C.V.'s less than 5%. Likewise, the lateral and sagittal moment-arms for each muscle were determined by averaging the three observed distances between the muscle centroid and vertebral centroid. Finally, the muscle vector directions in the lateral plane (Eq. 1.2) and sagittal plane (Eq. 1.3) were also averaged across each of the three observations.

Following the determination of the raw cross-sectional muscle areas, three separate corrections were made to the areas, when necessary. First, to correct for any degree of twisting of the subjects' torso while lying in the MRI machine, the muscle centroid locations were corrected by quantifying the location of the spinous process centroid at each scan level. It was assumed that if the subject was lying flat on the gantry table of the MRI with no twisting of the torso, there would be no difference in the lateral location of the vertebral body centroid and spinous process centroid, relative to the scan origin. Therefore, for any degree of twisting of the torso, the muscle centroid location was adjusted for the angle between vertebral body centroid and spinous process centroid. Secondly, for certain muscles that were not circular in shape, the muscle centroids actually lied outside of the muscle. Specifically, at certain levels of the spine, the muscle centroids for the latissimus dorsi, external obliques, and the internal obliques lied medial to the medial border of the muscle. Therefore, to obtain more realistic centroid locations for the calculation of the corrected cross-sectional areas of these muscles (described in the next step), a line was drawn from the vertebral body centroid, through the muscle centroid, to the estimated midpoint of the muscle. This estimated midpoint was then used as the vector location for the muscle for determination of the adjusted cross-sectional area (described next). Finally, the raw muscle cross-sectional area was adjusted so that the plane of the cross-sectional muscle area was perpendicular to the muscle vector direction. Since the MRI scan slices were perpendicular to the gantry table, and the muscles may not necessarily run parallel to the table, the resulting estimated cross-sectional areas of the muscles may be larger than the true cross-sectional area which would be perpendicular to the muscle vector direction. Therefore, the raw muscle cross-sectional areas at each scan level were adjusted by the sagittal and lateral muscle vector directions, using a general form of *equation 1.4*. For the muscles where the area centroid lay outside the muscle (i.e., latissimus dorsi, internal and external obliques), the adjusted vector directions (θ_{Lat} and θ_{Sag}) which were determined from the estimated midpoints of the muscles, were used to calculate the corrected cross-sectional areas.

$$Area_{Corr} = Area_{Raw} Cos(\theta_{Lat}) Cos(\theta_{Sag}) \qquad (Eq.\ 1.4)$$

where:

$Area_{Corr}$ = Corrected cross-sectional muscle area;
$Area_{Raw}$ = Raw cross-sectional area determined by outline from GyroView.
θ_{Lat} = Muscle vector angle in the lateral plane from one vertebral level to the next;
θ_{Sag} = Muscle vector angle in the sagittal plane from one vertebral level to the next;

The raw cross-sectional area, however, was multiplied by different vector values, depending on where in the spine the muscle is present. For the first level that the muscle was present (the most superior level), the raw cross-sectional area was multiplied by cosines of the sagittal and lateral vector for that level, using *equation 1.4*. For example, in some subjects, the most superior level where the rectus abdominis was first present was at the T_{12} level; therefore, the corrected cross-sectional area for the rectus abdominis at T_{12} was determined by:

$$Area_{Corr-T_{12}} = Area_{Raw-T_{12}} Cos(\theta_{Lat-T_{12}}) Cos(\theta_{Sag-T_{12}}) \qquad (Eq.\ 1.5)$$

where:

$Area_{Corr-T_{12}}$ = Corrected cross-sectional area at the T_{12} vertebral level;

$Area_{Raw-T_{12}}$ = Raw cross-sectional area at the T_{12} vertebral level, determined by the GyroView;

$\theta_{Lat-T_{12}}$ = Lateral muscle vector angle between the T_{12} and L_1 vertebral level;

$\theta_{Sag-T_{12}}$ = Sagittal muscle vector angle between the T_{12} and L_1 vertebral level.

For the same subjects, the second most superior level where the rectus abdominis was present would then have been L_1; however, to determine the corrected cross-sectional area of the rectus abdominis for the second level it was present, the raw cross-sectional area was multiplied by the cosines of the average of the muscle vector angles at the T_{12} and L_1 levels, for both the sagittal and lateral components:

$$Area_{Corr-L_1} = Area_{Raw-L_1} Cos\left(\frac{\theta_{Lat-T_{12}} + \theta_{Lat-L_1}}{2}\right) Cos\left(\frac{\theta_{Sag-T_{12}} + \theta_{Sag-L_1}}{2}\right) \qquad (Eq.\ 1.6)$$

where:

$Area_{Corr-L_1}$ = Corrected cross-sectional area at the L_1 vertebral level;

$Area_{Raw-L_1}$ = Raw cross-sectional area at the L_1 vertebral level, from the GyroView;

$\theta_{Lat-T_{12}}$ = Lateral muscle vector angle from the T_{12} to L_1 vertebral level;

θ_{Lat-L_1} = Lateral muscle vector angle from the L_1 to L_2 vertebral level;

$\theta_{Sag-T_{12}}$ = Sagittal muscle vector angle from the T_{12} to L_1 vertebral level;

θ_{Sag-L_1} = Sagittal muscle vector angle from the L_1 to L_2 vertebral level.

Likewise, the corrected cross-sectional area for the rectus abdominis when present at the next level (L_2), given that the muscle was present at L_1, was determined in the following manner:

$$Area_{Corr-L_2} = Area_{Raw-L_2} Cos\left(\frac{\theta_{Lat-L_1} + \theta_{Lat-L_2}}{2}\right) Cos\left(\frac{\theta_{Sag-L_1} + \theta_{Sag-L_2}}{2}\right) \qquad (Eq.\ 1.7)$$

where:

$Area_{Corr-L_2}$ = Corrected cross-sectional area at the L_2 vertebral level;

$Area_{Raw-L_2}$ = Raw cross-sectional area at the L_2 vertebral level, from the GyroView;

θ_{Lat-L_1} = Lateral muscle vector angle from the L_1 to L_2 vertebral level;

θ_{Lat-L_2} = Lateral muscle vector angle from the L_2 to L_3 vertebral level;

θ_{Sag-L_1} = Sagittal muscle vector angle from the L_1 to L_2 vertebral level;

θ_{Sag-L2} = Sagittal muscle vector angle from the L_2 to L_3 vertebral level.

Finally, to calculate the corrected cross-sectional area for the lowest level where the muscle was present (the most inferior level), using the example where the lowest level that the rectus abdominis was present was at S_1, the following equation was used:

$$Area_{Corr-S_1} = Area_{Raw-S_1} Cos(\theta_{Lat-L_5}) Cos(\theta_{Sag-L_5}) \qquad (Eq.\ 3.8)$$

where:

$Area_{Corr-S_1}$ = Corrected cross-sectional area at the S_1 vertebral level;

$Area_{Raw-S_1}$ = Raw cross-sectional area at the S_1 vertebral level, determined by the GyroView;

θ_{Lat-L_5} = Lateral muscle vector angle between the L_5 and S_1 vertebral level;

θ_{Sag-L_5} = Sagittal muscle vector angle between the L_5 and S_1 vertebral level.

Although the rectus abdominis was used as an example of how the corrected cross-sectional areas were calculated as a function of where it was present, *equations 1.5* through *1.8* were used for all the muscles to determine the corrected cross-sectional muscle areas perpendicular to the muscle vectors. Generally, the first level where a muscle was present (starting at the most superior level and working down), e*quation 1.5* was used; the last level that the muscle was present (the most inferior level), *equation 1.8* was used to calculate the corrected cross-sectional area. Finally, for all other levels in between the first and last level where the muscle was present, *equations 1.6 or 1.7* were used to calculate the corrected cross-sectional areas.

The moment-arms of the muscles at each level were determined by calculating the absolute difference between the muscle centroid and the vertebral body centroid, in both the sagittal plane and the lateral plane. The muscle centroids used for the calculation of the moment-arms were corrected for any torso twisting in the MRI machine, but were not corrected for those muscles where the centroids lay outside the inscribed muscle. Sign designations were given to the moment-arms, such that positive and negative values for the sagittal moment-arms represented anterior and posterior to the vertebral body centroid, respectively, and positive and negative values for the lateral moment-arms represent right and left sides of the vertebral body centroid, respectively.

Descriptive Statistics

Descriptive statistics (means and standard deviations at each vertebral level) were first generated for the corrected muscle cross-sectional areas perpendicular to the muscle vectors and corrected for any twisting in the MRI machine. This also included the cross-sectional areas corrected for the adjusted vectors where the centroids lay outside the muscle. Additionally, descriptive statistics for the cross-sectional areas for the vertebral bodies corrected for the spine vector directions, as well as the trunk cross-sectional areas for each scan level were also documented. Descriptive statistics were also generated for the corrected moment-arms for each muscle, both in the lateral and sagittal planes, as well as the muscle vector directions from level to level, in both the lateral and sagittal planes.

In the current EMG-assisted biomechanical model (Granata and Marras, 1993; Marras and Granata, 1995; Marras and Sommerich, 1991a,b), the muscle vector locations for the muscle origins and insertions are identified as a percentage of the trunk width for the lateral plane location, and the sagittal plane location is calculated as a percentage of the trunk depth, both measured at the iliac crest. The current database of 20 females and 10 males, however, allows other anthropometric measures to be explored; therefore, in addition to the vector locations being calculated as a function of trunk measurements about the iliac crest, the vector locations as a function of the trunk width and depth measured at the xyphoid process were also calculated, as well as a function of the body mass index (BMI).

Finally, since there may be individual differences as to what level along the spine, for each muscle, the largest muscle area exists, the distribution of the largest muscle area for each muscle by vertebral level for both males and females were determined.

As a benchmark, the results of the corrected cross-sectional areas and lateral and sagittal moment-arms were then compared with data from Chaffin et al. (1990) who examined elderly women, and McGill et al. (1993) who examined males. These comparisons consisted of the magnitude of the difference of similar measures, as well as the percent difference. Difficulty arose when comparing cross-sectional areas from level to level, since in both the Chaffin et al. (1990) and the McGill et al. (1993) study, the scan slices were set through the middle of the intervertebral disc, whereas in the current study, the scan slices were set through the estimated midpoint of the vertebral body. Therefore, the comparisons of muscle cross-sectional areas and moment-arms were off by one-half of a level. To account for the difference in the location of the slices, the area and moment-arm midpoint between adjacent slices of the data in the current study were determined, thus creating a more comparable area value to the Chaffin et al. (1990) and the McGill et al. study (1993). For example, averaging the muscle cross-sectional area at T_8 and T_9 of the current study, would allow a more logical comparison to the muscle cross-sectional areas of the T_8/T_9 scan slice from McGill et al. (1993).

Statistical Analyses

Linear regression techniques were used to predict the largest cross-sectional area for each muscle, for both males and females independently. The dependent variable consisted of the largest corrected cross-sectional muscle area, irrespective of the vertebral level. The individual independent variables for each regression equation consisted of the product of trunk width and trunk depth (cm^2) measured at the xyphoid process, the iliac crest and the trochanter, as well as the body mass index (kg/m^2). Statistical differences between the regression equations predicting cross-sectional areas for males versus females were also investigated using a hierarchical multiple linear regression approach (Neter et al., 1985). First, the combined male and female data were used to generate one regression equation using the individual independent variables of the trunk width multiplied by the trunk depth at the xyphoid process, the trochanter, and the iliac crest, as well as the body mass index. Then, a single regression equation was developed to predict the male and female cross-sectional areas independently, using a gender indicator variable. Finally, the effect of including a gender indicator variable was examined by testing to see if there was a significant increase in the multiple coefficient of variation

(R^2). If there was a significant difference, then the male and female regression equations were statistically different, which indicates that the male regression equation could not be used to predict the female cross-sectional muscle area.

Regression equations were also developed to predict the moment-arms of the muscles at the muscle origin and insertion points, for both the sagittal and lateral planes. In the EMG-assisted biomechanical model for males (Granata and Marras, 1993; Marras and Granata, 1995; Marras and Sommerich, 1991a,b), the origin was defined to exist at the L_5, where the specific insertion point for each muscle pair was a function of the magnitude of forward sagittal bending. Now that more data is available at more vertebral levels, the EMG-assisted model can be modified to account for the new data. Consequently, the muscle insertion and origin levels were defined slightly different. The insertion levels were T_8 for the latissimus dorsi and erector spinae, L_1 for the rectus abdominis and external obliques, and L_3 for the internal obliques. The origin levels were L_5 for the latissimus dorsi where the vector was projected from T_8 through L_2 down to the L_5 level; L_5 for the erector spinae and rectus abdominis; L_5 for the external obliques where the vector was projected from L_4 at a 45 degree angle, in the anterior and caudal direction in the sagittal plane, down to the L_5 level; and L_5 for the internal obliques where the vector was projected from L_3 through L_4 down to the L_5 level. The dependent variable consisted of either the lateral or sagittal moment-arm. The independent variables were the trunk width measured at the xyphoid process and the iliac crest when the lateral moment-arm was used as the dependent variable, whereas the trunk depth measured at the xyphoid process and the iliac crest was used for the independent variable when the dependent variable was the sagittal moment-arm. Additionally, the body mass index (kg/m^2) was also used as an independent variable for the moment-arm regression equations.

Since the insertion levels occur at different points depending on the muscle, it is important to be able to estimate the vertical distance of the insertion point above the L_5 vertebral level to be able to locate the insertion point of the muscles in three-dimensional space. Linear regression techniques were used to estimate the vertical distance of the insertion points above the L_5 level, for both females and males. Standing height was used as the dependent variable, where the dependent variable consisted of the vertical distance from L_3-L_5, L_1-L_5, and T_8-L_5, as determined from the MRI scans.

Differences between the right and left side cross-sectional muscle areas were statistically analyzed in two different ways. First, differences between the right and left side largest cross-sectional area (irrespective of which level it was located) for each muscle was assessed by using dependent sample *t*-tests, which were performed independently for each gender. Secondly, differences between the right and left sides at each specific vertebral level were assessed by performing an Analysis of Variance (ANOVA). The dependent variable consisted of the muscle cross-sectional area, and the independent variables included the subject, vertebral level, side (right or left), and a vertebral level by side interaction. Since each muscle was not always present at the same level for each subject, the data set was restricted to the levels where complete data existed, and where each subject had the muscle present between the two vertebral level endpoints. Thus, the latissimus dorsi muscle was restricted between T_8 and L_3, the erector spinae between T_8 and S_1, the rectus abdominis between L_1 and S_1, the external obliques between L_1 and L_4, the internal obliques between L_3 and L_4, the quadratus lumborum between L_2 and L_4, and the psoas major between L_2 and S_1. For subjects who did not have muscle areas present between the vertebral level endpoints listed above, they were excluded from the ANOVA. Females exhibited sporadic observations for different levels of the quadratus lumborum, therefore, it was excluded from the analysis as well. Post-hoc analyses consisted of Tukey pairwise comparisons on significant effects.

Finally, statistical differences between males and females for the cross-sectional areas, the lateral and sagittal plane moment-arms, as well as the muscle vector component directions at each vertebral level were determined by using *t*-tests with independent observations, with either equal or unequal variances where appropriate, with a significant difference indicated when $p \leq 0.05$.

Results

Anthropometric Measurements

The anthropometric data from the males and females are shown in Table 1.1. As expected, the mean value of each variable for the males were greater in magnitude than those of the females, although this difference was not tested statistically. When compared to other studies, the females in this study were much younger (25.0 vs 49.6 yrs), slightly taller (165.5 vs 163.1 cm), and lighter (57.9 vs 67.6 kg) than those females in the study by Chaffin et al. (11). The males in this study were slightly older (26.4 vs 25.3 yrs), were virtually the same height (175.9 vs 176.1 cm), and slightly lighter (79.8 vs 81.5 kg) than the males in the study by McGill et al. (15).

Corrected Cross-Sectional Muscle Areas

The corrected muscle cross-sectional areas for each of the muscles are shown in Tables 1.2 through 1.15. These tables list the mean and standard deviation of the cross-sectional area for each muscle, by vertebral level, where present. Also included in these tables are comparisons between the female cross-sectional areas from this study and the data from the females in the Chaffin et al. (11) study, comparisons between the cross-sectional areas from the males of this study and the data from males in a study by McGill et al. (15), as well as comparisons between the females and males of this study. The comparison between the different data sets consisted of the magnitude of the difference, as well as the percent difference, where the shaded cells represent significant differences between the male and female corrected cross-sectional muscle areas.

As expected, the cross-sectional areas of the females were smaller than those of the males, however, this difference differed as a function of the muscle of interest. The female latissimus dorsi areas (Tables 1.2 and 1.3) ranged from 36% to 49% smaller than that of the males, with an average of 41.1%, and were all significantly smaller than the male muscle areas. Similarly, the female erector spinae areas (Tables 1.4 and 1.5) ranged from 38% to 48% smaller than that of the males, with an average of 40%, again with the female areas being significantly smaller at every level. The female rectus abdominis areas (Tables 1.6 and 1.7) ranged from 22% to 42% smaller than the males, with an average of 32.2%, where the lowest two levels (L_5 and S_1) ranged from 40% to 42% smaller than the males. All levels except two for the left rectus abdominis were significantly smaller than the male cross-sectional areas. The female external obliques (Tables 1.8 and 1.9) ranged from 20% to 41% smaller than the males external obliques, with an average of 31.3% across all levels. All but the cross-sectional area at L_5 were significantly smaller than the males, with T_{12} also smaller for the right side as well. The internal obliques (Tables 1.10 and 1.11) of the females showed a wide range of area in comparison to the males, ranging from 6% larger to 45% smaller than the males, with the female areas at L_3 and L_4 significantly smaller than the males for both right and left sides. The largest difference between the female and male cross-sectional area existed for the psoas major muscle (Tables 1.12 and 1.13), where the female area ranged from 37% to 56%, averaging 49.1% smaller than the male psoas major cross-sectional area. Finally, the female quadratus lumborum (Tables 1.14 and 1.15) ranged from 34% to 61% smaller than the male area, with an average of 43.8% smaller. All levels except L_1 which had very few observations, were significantly smaller than the male cross-sectional areas.

The cross-sectional area of the female vertebral body (Table 1.16) was consistently smaller than that of the males, ranging from 20% to 27% smaller, averaging 24.4% smaller than that of the males. The trunk cross-sectional areas for the females (Table 1.17) ranged from 34% smaller to 6% smaller. The largest difference was at T_8 (34% smaller than the male trunk area), and the difference consistently decreased while descending the spine caudally to the smallest difference (6% smaller) at the S_1 level.

Comparisons between the results of this study and similar studies from the literature are also shown in Tables 1.2 through 1.17. Comparisons between the corrected cross-sectional areas by level between the males of this study and the male subjects from McGill et al. (15) found that across all muscles and levels, the absolute difference averaged 26.6%. After making the one-half vertebral level adjustment to the current dataset, the absolute percent difference dropped to 16.1%, ranging from 6.4% (down from 11.7% without the adjustment) for the rectus abdominis to a 35.7% difference (down from 48.3% without the adjustment) for the internal obliques. Thus, adjusting for the difference in the scan levels between the two studies resulted in fairly good comparability for most of the muscle cross-sectional areas between the two studies.

The study on elderly females by Chaffin et al. (1990) also set the scan slices through the intervertebral disc, at the L_2/L_3, L_3/L_4, and L_4/L_5 levels. When comparing the cross-sectional muscle area of the current study from the L_2, L_3, and L_4 levels with the muscle areas at the L_2/L_3, L_3/L_4, and L_4/L_5 levels, respectively, from the Chaffin et al. study (1990), the absolute percent difference was 30.6%. When using the midpoint adjusted area data for the current study, the absolute percent difference dropped only to 27.7%, ranging from 8.2% difference for the psoas major (down from 22% without the adjustment), to a 95% difference for the latissimus dorsi (up from 88% without the adjustment). Generally, the cross-sectional areas for the latissimus dorsi, rectus abdominis, and the external obliques for the current study were larger in comparison to the data from Chaffin et al. (1990), whereas, the cross-sectional areas for the erector spinae, internal obliques, psoas major and quadratus lumborum were smaller than the cross-sectional areas of the females in Chaffin et al. (1990).

Lateral Plane Moment-Arms

The corrected lateral moment-arms for the males and females, as well as those documented in other studies for comparison purposes are shown in Tables 1.18 through 1.31. The male moment-arms were significantly greater than the females at all levels for the latissimus dorsi and left erector spinae, and all but the lower three levels for the right erector spinae. Only the right rectus abdominis resulted in significant differences between males and females, whereas none of the levels were different on the left side. Five of the six levels resulted in significantly larger male lateral moment-arms for the external obliques and the psoas major, and three of the four levels resulted in significantly larger male lateral moment-arms for the quadratus lumborum. Three of the four levels for the right internal oblique and two of the for levels for the left internal oblique resulted in larger male lateral moment-arms.

The male lateral moment-arms of this study were very consistent with those reported in McGill et al. (1993), with an average absolute difference of 8.0%, which dropped to 5.5% when adjusting for the one-half level vertebral difference. The absolute percent difference between the lateral moment-arms were slightly larger when comparing the female data of the current study to those of the Chaffin et al. (1990) study. Without adjusting for the one-half vertebral level difference, the absolute percent difference was 11.2%, where the difference dropped to 8.6% when adjusting for the vertebral level difference. Generally, the moment-arms were smaller for all muscles except for the erector spinae, which were very similar to those of the elderly females in the Chaffin et al. (1990) study.

Sagittal Plane Moment-Arms

The corrected sagittal moment-arms for the males and females, as well as those documented in other studies for comparison purposes are shown in Tables 1.32 through 1.45. Compared to the lateral moment-arms, there were fewer significant differences between males and females. For the latissimus dorsi, only the moment-arm at L_3 was significantly larger for the males; the remaining levels resulted in no significant differences. The majority of levels, however, for both sides of the erector spinae showed the males to have significantly larger sagittal moment-arms than the females. Only the sagittal moment-arm at the S_1 level was not significantly different between males and females for both right and left rectus abdominis. The results were mixed for the external and internal obliques as well as the psoas major; the left side of each muscle, however, did result in more significant differences than the right side, with the males exhibiting larger moment-arms than the females, except for the psoas major. Finally, there were no significant difference between the sagittal moment-arms for both the right and left quadratus lumborum.

The absolute percent differences between the sagittal moment-arms for the males of the current study and those of McGill et al. (1993) were much larger than the differences of the lateral moment-arms. Generally, the absolute percent difference between the two studies was 32.8%, which dropped to 23.6% when adjusting the data of the current study for the one-half vertebral level difference. Extremely large percent differences exist for the external obliques and the internal obliques, with the upper levels of the males in the current study having larger moment-arms and the lowest level having smaller moment-arms. Large percent differences also resulted for the psoas major (75.2% and 52.2% for the right and left side, respectively), with the moment-arms for the males in the current study being smaller at each level (Tables 1.42 and 1.43). Aside from the left latissimus dorsi, (Table 1.33), the rest of the muscles resulted in absolute percent differences between 6.6% and 11.4% (5.6% and 6.3% when adjusting for the one-half vertebral difference).

The absolute percent difference between the females of the current study and those from Chaffin et al. (1990) was fairly large (32.0%), although this large difference was primarily driven by large percent differences between the psoas major. When accounting for the one-half vertebral difference, the absolute percent difference drops to 16.7%, where the difference between the sagittal moment-arms of the external and internal obliques increases the percent difference.

Muscle Vector Directions

The muscle vector directions for both males and females, as well as in both the lateral and sagittal plane are shown in Tables 1.46 through 1.59. Additionally, the results of the *t*-tests for the statistical difference between the males and females by muscle and vertebral level are also shown. For the latissimus dorsi (Tables 1.46 and 1.47), the only significant difference between vector angles was for the left latissimus dorsi, where the sagittal vector angle was statistically greater for the females than the males. For the erector spinae (Tables 1.48 and 1.49), there were significant differences between males and females at L_2 and L_3 for the left and right muscles for the lateral vector, and for the T_{10} and T_{11} vectors for both right and left muscles, respectively, for the sagittal vector, as well as L_2, L_3, and L_5 for the left erector spinae only. Several differences existed between males and females for the rectus abdominis (Tables 1.50 and 1.51). The vector angle differences at L_4 and L_5 ranged from 8.7 to 14.0, with the female vector angles being more posterior in the sagittal plane than the males. For the right side, L_4 showed significant differences for both the sagittal and lateral vectors; for the left rectus abdominis, L_5 was significant for both the sagittal and lateral vector, but T_{12} and L_3 was significant for only the lateral vector. For the external obliques (Tables 1.52 and 1.53), the lateral vector at L_3 was significant for both the right and left sides, with the females exhibiting a larger lateral direction than the males. Additionally, the lateral vector at T_{12} was significant for only the left external oblique. For the sagittal vector, the only significant difference was at T_{12}. There were no significant sagittal vectors for the internal obliques (Tables 1.54 and 1.55), however, the lateral vectors at L_4 and L_3 were significant for the right and left internal obliques, respectively, with the females exhibiting a greater lateral direction of the muscle than the males There were no significant differences for the right psoas major (Table 1.56), however, the L_5 vector was significant in both the sagittal and lateral plane for the left psoas major (Table 1.57) as well as L_2 for the sagittal vector. For the quadratus lumborum (Tables 1.58 and 1.59), both the L_2 and L_3 vectors in the sagittal plane were significant for both the right and left sides, with females exhibiting a greater anterior angle than males between the L_2 and L_3 vertebral levels. The males, however, had a greater anterior angle than the females from the L_3 to L_4 vertebral levels. Finally, the females exhibited greater anterior angles than males between the T_{10} and T_{11}, and the T_{11} and T_{12} vertebral levels (Table 1.60), although the differences were only 4.3 and 3.2 degrees, respectively. The females had a significantly larger posterior vector angle between L_5 and S_1 than the males, with the females angle being 6.6 degrees greater in the posterior direction than the males.

Prediction of Largest Muscle Areas

Summary tables of significant regression equations for predicting largest cross-sectional areas, by muscle and gender are shown in Tables 1.61 through 1.64. The regression equations predicting cross-sectional area for the muscles are shown in Tables 1.65 through 1.71, with each table documenting a separate muscle. For the latissimus dorsi, use of the anthropometric measurements at the xyphoid process resulted in significant regression equations for females, with 34.9% to 38.8% of the variability in the cross-sectional area explained. Similarly, for the males, the xyphoid process resulted in a significant regression equation predicting the left latissimus dorsi, and a marginally significant equation predicting the cross-sectional area using the largest of the right and left muscle ($p=0.0553$). None of the other anthropometric variables (i.e., iliac crest, trochanter, and BMI) resulted in significant regression equations predicting latissimus dorsi cross-sectional area. When comparing the male and female regression equations, there were no significant difference between the male and female regression equations for those gender specific equations which significantly predicted muscle cross-sectional areas.

The use of BMI and the xyphoid process measurements resulted in significant equations for the female erector spinae (Table 1.66), with R^2's between 0.44 and 0.445 for the xyphoid process, and between 0.474 and 0.491 for the BMI. For the male erector spinae areas, use of the BMI and measurements about the trochanter resulted in significant regression equations, with R^2's between 0.407 and 0.417 for the trochanter, and 0.454 and 0.487 for the BMI. When comparing the gender specific regression equations, each regression equation (by anthropometric variable) for the females was significantly different than the regression equations for the males, thus indicating that the regression equations cannot be used interchangeably to predict male or female muscle erector spinae cross-sectional muscle area.

For prediction of the rectus abdominis cross-sectional muscle areas (Table 1.67), the use of the BMI and measurements about the xyphoid process resulted in significant regression equations for the females, with R^2's ranging from 0.345 to 0.37 using the xyphoid process measurements and 0.23 and 0.277 for the BMI. The use of the BMI resulted in significant regression equations for predicting male rectus abdominis areas (including the right and left side, as well as the average of the largest right and left side), with R^2's ranging from 0.436 to 0.504. The use of measurements about the xyphoid process resulted in a significant regression equation for predicting the right rectus abdominis area ($R^2=0.475$), and a marginally significant equation predicting the average of the largest right and left sides ($p=0.0567$, $R^2=0.383$). Investigation of differences between regression equations predicting male and female muscle areas resulted in no significant differences between the gender specific equations.

The use of the measurements about the xyphoid process resulted in significant regression equations predicting the right, left, and average of the right and left largest external oblique cross-sectional areas, for both females and males (Table 1.68). The R^2's ranged from 0.261 to 0.403 for females, and 0.527 and 0.588 for males. The male and female regression equations were significantly different from each other when predicting the left cross-sectional area, and also the average of the right and left largest cross-sectional areas, and was marginally significant when predicting the right external oblique area (p=0.0579). Thus, the individual regression equations for the males and females are not interchangeable for predicting the largest cross-sectional areas of the external obliques.

The use of the BMI and measurements about the xyphoid process resulted in significant regression equations predicting the cross-sectional area of the internal obliques for the females (Table 1.69), with R^2's ranging from 0.565 to 0.613 when using the xyphoid process, and ranging from 0.433 to 0.557 when using the BMI. Only the xyphoid process measurements resulted in significant regression equations for predicting male internal obliques cross-sectional areas, and only for the left (R^2=0.491) and average of right and left largest muscles (R^2=0.439) areas, although the right side was close to being significant (p=0.0862). When comparing the gender specific regression equations, there were no significant differences between the gender specific equations when using measurements about the xyphoid process, however, the use of the BMI did result in significant differences in gender specific equations for the left and average of the right and left cross-sectional areas.

As shown in Table 1.70, none of the anthropometric variables used to predict the psoas major cross-sectional muscle area resulted in significant regressions, for either side, nor for either females or males. The use of measurements about the xyphoid process resulted in significant regression equations predicting the cross-sectional area of the quadratus lumborum (Table 1.71) for the right and left sides, as well as the average of the largest right and left areas for the females only (R^2's ranged from 0.224 to 0.326). The measurements about the trochanter resulted in significant regression equations predicting the right and left areas as well as the average of the right and left areas for males (R^2's ranged from 0.450 to 0.531). Finally, the male and female regression equations were significantly different from each other for each cross-sectional area predicted, as well as for each anthropometric variable used to predict the areas.

Prediction of Muscle Moment-Arms

The prediction of the moment arms in both the lateral and sagittal plane, from external anthropometric measurements are shown in Tables 1.72 through 1.81. For the latissimus dorsi (Tables 1.72 and 1.73), the trunk depth and width measures at the iliac crest did not result in any significant associations. Generally, the xyphoid process resulted in several significant predictions of moment-arms, with more for the right side than the left. For the erector spinae (Tables 1.74 and 1.75), only the xyphoid process trunk depth measurement was significant for the female when predicting the sagittal moment-arm at the insertion level of T_8. No other prediction equations were significant for the right or left side, for the origin or insertion, as well as female or male. The regression equations predicting lateral and sagittal moment-arms for the rectus abdominis (Tables 1.76 and 1.77) resulted in several significant associations, however, mostly for males. For the females, only the trunk depth measured at the xyphoid process for the insertion of the right rectus abdominis was significant, whereas the trunk depth and width measured about the xyphoid process were significant for the insertions for the left side, as well as the trunk depth measure at the iliac crest for the insertion of the left side. The trunk width measures at the xyphoid process and the BMI resulted in significant regressions predicting the lateral moment arms for both the right and left external obliques for females at the L_1 level (Tables 1.78 and 1.79); only the trunk width at the iliac crest was significant for the males for the lateral moment-arm for the right external oblique of the males, whereas the trunk width at the xyphoid process and the BMI were significant for the lateral moment arm at L_1 for the left external oblique of the males. Finally, the trunk width and depth measures at the xyphoid process and the BMI were significant predictors of both lateral and sagittal moment arms for the right and left internal obliques for the females at the L_3 level (Tables 1.80 and 1.81).

Muscle Vector Locations

The locations of the lateral and sagittal components of the muscle vectors at the origin specified by the EMG-assisted model (L_5) for each of the five pairs of muscles are shown in Table 1.82, where the locations of the muscle vectors at the different insertion levels are shown in Table 1.83. Each of the values in these two tables represents the coefficient in which the external anthropometric measure must be multiplied by to determine the distance of the vector from the vertebral body centroid in the lateral or sagittal plane. The vector location distances from the spine are shown as a function of the trunk width and depth measures at the xyphoid process and the iliac crest, where the trunk depth measure corresponds to the vector location in the sagittal plane and the trunk width measure corresponds to the vector locations in the lateral plane. The vector locations for the origins (Table 1.82) are all very comparable whether using the iliac crest or the xyphoid process external anthropometric measures. Viewing the insertion locations for both the iliac crest and xyphoid process (Table 1.83), the coefficients are all very similar, where the largest differences between the two measures occurs for the male lateral locations of the latissimus dorsi and the female sagittal locations of the rectus abdominis. Slight differences exist between the male and female vector locations for the muscle origins (Table 1.82), where the largest differences exist for the xyphoid process measures for the internal obliques for the lateral vector locations, and the xyphoid process measures for the latissimus dorsi and erector spinae for the sagittal vector locations. Slight differences also exist between the male and female insertion vector locations (Table 1.83), where the largest differences occur between the iliac crest coefficients for the rectus abdominis in the sagittal plane (females exhibiting a smaller ratio of A/P moment-arm to trunk depth than males), and smaller differences for the external obliques, also using the iliac crest. The resulting regression equations to predict the vertical location above the L_5 vertebral level for the muscle insertions are shown in Table 1.84. Generally, the equations for the female distances resulted in moderate R^2s (0.144 to 0.392), with the T_8-L_5 and L_1-L_5 equations resulting in significant prediction, and the equation predicting L_3-L_5 distance moderately significant (p=0.0989). The equations for the males were all significant, with more than half of the variability in the distance from the L_5 vertebral level to the insertion point explained by the standing height of the males (R^2s ranging from 0.527 to 0.639).

Differences between Right and Left Muscle Areas

The mean difference between the largest right and left muscle cross-sectional areas, for both males and females are shown in Table 1.85. Both males and females exhibited significantly larger right side than left side for the latissimus dorsi. The external obliques were significantly larger on the right side than the left for the females, where the left side was significantly larger for the psoas major and quadratus lumborum. No other significant differences between the sides existed for the males. The Analysis of Variance on the differences between the right and left side cross-sectional areas by vertebral level for both females and males are shown in Table 1.86. There were significant differences between the right and left cross-sectional areas for the latissimus dorsi for both the females and males, and the psoas major for only the females. Post-hoc tests found that these differences occurred at the T_8 through T_{12} levels for the females and T_8 through T_{10} levels for the males for the latissimus dorsi, with the right side being larger than the left side (Table 1.87). For the psoas major muscle, post-hoc tests found that the left side was significantly larger than the right side for levels L_4 and L_5 for the females. The magnitude and percent difference between the right and left sides for each muscle group are shown in Table 1.88 for the females, and 1.89 for the males. Significant differences found from the Tukey pairwise comparisons are also shown, which correspond to the significant levels and sides shown in Table 1.87.

Distribution of the Largest Muscle Area

The distribution of the largest muscle area for both the right and left pairs of each muscle, as a function of vertebral level are shown in Tables 1.90 through 1.96. Although there was some variability between the right and left pairs of each muscle as far as which vertebral levels had the highest percentage of the largest areas, as well as which levels had the largest muscle area present, general trends did exist. For the latissimus dorsi (Table 1.90), the largest muscle area was mostly at the T_8 level, with very few occurring at T_9. The largest areas for the erector spinae were generally split between L_3 and L_4, with a few located at L_2 and L_5 (Table 91). The largest muscle area location for the rectus abdominis showed a large variability for both males and females (Table 92). For the females, the largest area was split between L_4, L_5 and S_1 for the right side, and L_4 and L_5 for the left side, with a few at several other levels. For the males, 70% of the largest areas were at L_5 for both the right and left sides. For both male and females, the largest external oblique area for the right and left sides were located at L_4, with a few also located at L_2, L_3, and L_5 (Table 93). Similarly, for the internal obliques (Table 94), the majority of the largest muscle areas were also located at L_4, with a few also located at L_3 and L_5. Finally, for both the quadratus lumborum (Table 95) and the psoas major (Table 96), the largest areas were located at L_4 for the majority of subjects, with L_2, L_3 and L_4 having very few for the quadratus lumborum and L_5 having a few for the psoas major.

Discussion

Female Data

The database of muscle cross-sectional areas, moment-arms from the vertebral centroid, and muscle vector angles represent the largest and most complete database for the females to date, as well as for male to female comparisons. The female areas for the latissimus dorsi, rectus abdominis and external obliques are larger than those quantified by Chaffin et al. (1990), whereas the areas were smaller for the erector spinae, internal obliques, psoas major and quadratus lumborum were smaller than Chaffin et al. (1990), even after adjusting the areas by one-half of a vertebral level. The scans in Chaffin et al. (1990) were taken by computed tomography (CT), and the separation between muscles or the muscle borders may not have been as clear as when using MRI technology. Additionally, the female subjects in Chaffin et al (1990) were elderly females, with a mean age of 49 yrs, compared to 25.3 yrs in the current study, which may show up as muscle atrophy in the elderly population for some of the muscles.

Differences also existed for the moment-arms in both planes between the females from Chaffin et al. (1990) and the current study. Generally, all the lateral plane moment-arms in the current study were smaller than from Chaffin et al. (1990), with the one-half level adjustment making better comparisons only for the psoas major and quadratus lumborum. The sagittal moment-arms for the current study showed no apparent patterns. The erector spinae of the current study were slightly smaller than those in Chaffin et al. (1990), with the one-half level adjustment not making much difference for comparability, and the rectus abdominis were smaller at the lower two levels of comparison for the current study, again the one-half level adjustment not making much difference. The external and internal obliques, as well as the psoas major were both smaller and larger, depending on the level of comparison, with the one-half level of adjustment decreasing the differences between the two studies. The differences between the moment-arm distances between the two studies may have been influenced by the different scan techniques, with Chaffin et al (1990) using CT technology versus MRI in the current study. The use of MRI technology, again, may increase the clarity of the muscle border and spine border locations, which can affect the resulting distances between the centroids of the objects of interest. Differences in the moment-arm distances may also exist due to possible age-related differences such as increases in body mass. The females in Chaffin et al. (1990) average 49.6 years compared to 25.0 yrs for the current study, with the elderly females being shorter (163.1 cm vs 165.5 cm) and heavier (67.6 kg vs 57.9 kg) than the females of the current study. This indicates that the elderly females had a higher BMI, or more soft tissue, which may increase the distance between the spine and certain muscles, depending on the deposit locations of adipose tissue. The larger BMI of the elderly female populations is also consistent with observation that the trunk cross-sectional areas at the three levels of comparison, with the females of the current study averaging 23% less cross-sectional area at the levels of comparison than the older females in the Chaffin et al. (1990) study.

Male Data

The largest database for comparison purposes to the male data in the current study was from McGill et al. (1993), which quantified the muscle cross-sectional areas and moment-arms from T_5/T_6 through L_5/S_1, also with the use of MRI technology. Generally, when correcting for the one-half of a level difference of the location of the scan slices, the cross-sectional areas of similar muscles were fairly consistent between the two studies for the latissimus dorsi, erector spinae, rectus abdominis (Tables 1.2 through 1.7), and the psoas major (Tables 1.12 and 1.13), with average percent differences ranging from 6% to 12.8% between similar muscles at similar levels. Larger differences existed between the external and internal obliques (Tables 1.8 through 1.11), as well as the quadratus lumborum (Tables 1.14 and 1.15), between the two studies, with the cross-sectional areas from the current study consistently smaller at common scan levels.

Comparisons of the lateral moment-arms between the males of the current study and those of McGill et al. (1993) found that the moment-arm distances were all very comparable, with most of the differences ranging from an average of 2.8% difference (left psoas major) to a 6.2% difference (left rectus abdominis). Only the right rectus abdominis and left quadratus lumborum resulted in larger differences between the two studies (15.5% and 9.0%, respectively). The differences between the sagittal moment-arms, however, were much higher between similar muscles and scan levels between the males from the current study and those of McGill et al. (1993). The erector spinae and rectus abdominis sagittal moment-arms were very similar between the two studies. However, the left latissimus dorsi (30.8%), the external obliques (14.3% and 25.2%, for right and left, respectively), internal obliques (26.7% and 30%, for right and left, respectively), and the psoas major (81.8% and 53.8%, for right and left, respectively), had fairly large absolute percent differences. The large percent differences between the psoas major can be attributed to the small moment-arms, where slight differences would result in large percent differences. The large differences between the obliques, however, may have resulted from the differences in the cross-sectional areas, or the distribution of the cross-sectional areas. The upper levels (L_2 and L_3) resulted in larger sagittal moment-arms for the males in this study, indicating that the muscle centroid was located further anteriorly to the spine in the current study than those in the McGill et al. study (1993), possibly due to differences in the location of the outlined muscles.

Females vs. Males

As expected, the comparisons of the cross-sectional areas, lateral and sagittal moment-arms, as well as the muscle vector directions in both the lateral and sagittal planes resulted in many significant differences between the two genders, with males exhibiting larger measures than the females. The importance of these differences may, however, be illuminated when trying to predict the cross-sectional areas of the males and females based upon external anthropometry, or in other words, normalizing the cross-sectional areas, as well as the moment-arms in both the lateral and sagittal planes, to measurable external anthropometry variables. The current EMG-assisted biomechanical model (Granata and Marras, 1993; Marras and Granata, 1995; Marras and Sommerich, 1991a,b) uses coefficients which are multiplied by the trunk width to estimate the lateral moment-arms, and trunk depth to estimate the sagittal moment-arm, where the trunk width and depth are measured at the iliac crest. Additionally, the product of the trunk width and trunk depth measured at the iliac crest is used to predict the cross-sectional areas of the trunk muscles. However, as shown in Tables 1.65 through 1.69, use of trunk width and trunk measurements at the iliac crest to predict the cross-sectional areas of each of the 10 trunk muscles, as well as the average of the right and left muscles for each of the five pairs of muscles resulted in no significant regression equations for females; for the males, the measures about the iliac crest resulted in a marginally significant equation prediction the average of the largest right and left largest cross-sectional area for the internal obliques ($p=0.0584$), as well as a marginally significant equation predicting the cross-sectional area of the left internal oblique ($p=0.0589$). Typically, the measures about the xyphoid process did much better at predicting the largest cross-sectional areas, for both males and females. As shown in Table 1.63, use of the xyphoid measures resulted in significant prediction equations ($p \leq 0.05$) for all but the erector spinae, with the erector spinae equation being marginally significant ($p=0.0903$) for the males. For the females (Table 1.61), the measures about the xyphoid process resulted in significant prediction equations for cross-sectional areas for each of the five muscle pairs, as well as each of the ten individual muscles (Table 1.62). When using measures about the xyphoid process, the percent of the variance of the cross-sectional area explained were somewhat modest, however, ranging from 35.6% to 61.3% for the average of the right and left muscles for the females, and 26.1% to 59.1% for each of the individual muscles for the females. These values, however, are much higher than when using the measures about the iliac crest, where 1.4% to 9.5% of the variance of the cross-sectional area was explained when predicting the average of the largest right and left muscles; when predicting the individual muscle cross-sectional areas, only 0.5% to 16.4% of the variance was explained for females using the measures about the iliac crest. Thus, the use of measures about the xyphoid process provided better prediction of the largest cross-sectional muscle areas for both the females and the males than when using the iliac crest anthropometric measurements.

The use of measures about the iliac crest to predict moment-arms in the lateral and sagittal plane showed mixed results for the males, and very poor results for the females. For the males, the measures about the iliac crest and xyphoid process resulted in no significant prediction equations for the right and left pairs of the latissimus dorsi and erector spinae for the sagittal moment-arms at both the origin and insertion levels, as well as no significant regression equations for the internal and external obliques at the insertion levels (L_3 for internal obliques, and L_1 for external obliques). The rest of the muscles showed inconsistent associations or no associations to trunk width or trunk depth measurements either at the iliac crest or the xyphoid process. For the females, the use of trunk depth and width measures from the iliac crest resulted in only one significant regression equation, which was for predicting the sagittal moment-arm for the left rectus abdominis. The measures about the xyphoid process resulted in more significant prediction equations, but none for the erector spinae and rectus abdominis (except for the right erector spinae and right rectus abdominis insertion level sagittal moment-arm), as well as the latissimus dorsi sagittal moment-arms. Therefore, the use of measures about the xyphoid process to predict moment-arms, although not consistent across all muscles, does result in more significant predictions equations for the females as well as the males.

Most of the male cross-sectional areas were significantly larger than those of the females, however, when normalizing to external anthropometric measures of the trunk width multiplied by the trunk depth, fewer differences resulted. Specifically, the separate regression equations predicting cross-sectional areas were significantly different for the erector spinae, external and internal obliques, but not for the rectus abdominis or latissimus dorsi muscles. Given that the erector spinae are the major extensor muscles which raise the torso during lifting activities, and that the external and internal obliques are involved during twisting activities, it is necessary that the development of the EMG-assisted biomechanical model for females be developed using the female specific regression equations predicting cross-sectional muscle areas.

Although several levels for the erector spinae and rectus abdominis resulted in significant differences between the muscle vector directions, many were different by only 5 to 6 degrees. There was an apparent trend, however, of the females having larger posterior muscle vector angles for both right and left erector spinae at the L_5 to S_1 levels of 7.6 and 12.3 degrees, respectively. This observation combined with the females exhibiting greater posterior sagittal vector angle of the vertebral body centroid between L_5 and S_1 suggest that females have greater lordosis than males, which has been suggested by other researchers (Cooper et al., 1992). Larger vector angle differences between males and females in the sagittal plane were observed for the rectus abdominis at the lower vertebral levels, ranging from 8.7 to 14 degree difference, with the females rectus abdominis possessing greater posterior angles than the males (Tables 1.50 and 1.51). The external obliques also exhibited greater lateral angles for the females than the males between the L_3 and L_4 vertebral levels, with differences of about 6 degrees (Tables 1.52 and 1.53). The internal obliques also showed larger differences in the lateral vector angles for the lower levels as well (L_3 and L_4), with differences ranging from 5.6 to 14.3 degrees, with the females exhibiting vector angles more lateral from the L_3 to L_5 vertebral levels than the males (Tables 1.54 and 1.55). Thus, these differences in vector angles between males and females near the L_5 vertebral level indicates that the contribution of the external and internal obliques, as well as the rectus abdominis and erector spinae muscles, to the loading on the spine may be different between the males and females for similar motions and exertion levels.

Muscle Vector Locations

As shown in Tables 1.82 and 1.83, the muscle vector locations for males and females, as a function of external anthropometric measurements are given for each of the ten muscles used in the EMG-assisted biomechanical model, as a function of external anthropometric measurements. Generally, there were very small differences between the coefficients determined from the iliac crest and from the xyphoid process at the muscle origins (L_5), with a few larger differences existing between the coefficients of the iliac crest and xyphoid process at the insertion levels, for the males latissimus dorsi, and the female rectus abdominis. Differences between the coefficients for males and females were very small, generally in the 1 to 3% range. A large difference existed at the origin level for the internal obliques, with the females vector location lying more lateral than the males vector location when the xyphoid process trunk width measurement was used. This is consistent with the observation of females possessing greater hip breadth than men (9), as well as the observation of the females in this study exhibiting larger lateral vector angles in the lower lumbar area than males (Tables 1.54 and 1.55). Additionally, the female insertion coefficients (at the L_1 level) were smaller than the males for the rectus abdominis in the sagittal plane when using the trunk depth measured at the iliac crest as a reference (Table 1.83). This is consistent with the findings of Reid and Costigan (1987) who found the females exhibited smaller sagittal moment-arm to trunk depth ratios than males, with the trunk depth measured at the L_5 level. Thus, these gender differences in muscle vector location may indicate that the loading directions may be different depending on the direction of the exertion (e.g., flexion for the rectus abdominis or twisting or extension for the internal obliques), or as increases in coactivity occur, which would influence the loading on the spine (Granata and Marras, 1995).

Right and Left Side Symmetry

Results of the statistical analysis revealed several differences between the cross-sectional muscle areas for both the males and females. Both males and females exhibited significantly larger right side latissimus dorsi muscle area when considering just the largest cross-sectional areas. Additionally, there existed statistically larger right side than left side cross-sectional areas for both males and females for the more superior levels scanned (Tables 1.85, 1.88, and 1.89). The findings of McGill et al. (1993) also support the existence of larger right than left side cross-sectional areas, although this difference was not tested statistically, and this was only for males. Thus, the influence of the force generating capability of the muscles may be influenced by the direction of the exertion (right or left side), as well as the type of exertion which would have an influence on the muscle groups recruited.

Table 1.1. Female and Male Subject mean (s.d.) anthropometric measurements.

Gender	Age (yrs)	Height (cm)	Weight (kg)	Trunk Depth at Trochanter (cm)	Trunk Width at Trochanter (cm)	Trunk Depth at Iliac Crest (cm)	Trunk Width at Iliac Crest (cm)	Trunk Depth at Xyphoid Process (cm)	Trunk Width at Xyphoid Process (cm)	Trunk Circumference at Iliac Crest (cm)	Right Trochanter Height (cm)	Left Trochanter Height (cm)	Body Mass Index (kg/m^2)
Female (N=20)	25.0 (7.2)	165.5 (5.9)	57.9 (6.4)	23.1 (2.1)	33.7 (1.9)	19.8 (2.1)	28.0 (2.4)	18.4 (1.8)	27.0 (1.9)	76.0 (5.7)	85.3 (9.0)	86.7 (5.0)	21.2 (2.5)
Male (N=10)	26.4 (5.5)	175.9 (9.1)	79.8 (13.3)	25.4 (2.1)	34.8 (2.4)	22.3 (2.2)	30.3 (2.2)	22.9 (2.2)	32.4 (2.0)	86.8 (7.5)	89.0 (6.8)	88.8 (6.6)	25.7 (2.3)

Table 1.2. Mean (s.d.) trunk muscle cross-sectional area of the Right Latissimus Dorsi. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of area and as a percent of the literature values [ ]. Absolute and percent differences in muscle areas between male and female subjects are also shown.

Right Latissimus Dorsi - Cross-Sectional Area

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	Difference[D] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Difference[D] [% Diff.]	Female vs Male[B,C] [% Diff.]
T8	2169 (499)	1581 (159)	588 [37]	480 [30]	1321 (455)				-848 [-39]
T9	1954 (440)	1458 (269)	496 [34]	365 [25]	1144 (519)				-810 [-41]
T10	1692 (541)	1368 (330)	324 [24]	207 [15]	971 (478)				-721 [-43]
T11	1458 (462)	1254 (281)	204 [16]	77 [6]	865 (495)				-593 [-41]
T12	1204 (375)	1014 (264)	190 [19]	26 [3]	742 (426)				-462 [-38]
L1	877 (239)	717 (260)	160 [22]	40 [6]	534 (298)				-343 [-39]
L2	637 (197)	429 (202)	208 [48]	32 [7]	347 (194)	120 (40)	227 [162]	127 [105]	-290 [-46]
L3	285 (154)	232 (192)	53 [23]	-24 [-10]	146 (61)	130 (40)	16 [12]		-139 [-49]
L4	131 (22)					130 (50)			
L5									
S1									

A = Square mm;
B = Female minus Male (Square mm);
C = Shaded cells represent significant difference between females and males (p≤0.05);
D = Comparisons based on data adjusted one-half of a vertebral level.

Table 1.3. Mean (s.d.) trunk muscle cross-sectional area of the Left Latissimus Dorsi. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of area and as a percent of the literature values [ ]. Absolute and percent differences in muscle areas between male and female subjects are also shown.

Left Latissimus Dorsi - Cross-Sectional Area

Level	OSU Male mean^A (s.d.)	McGill et al., (1993) mean^A (s.d.)	Difference^A [% Diff.]	Difference^D [% Diff.]	OSU Female mean^A (s.d.)	Chaffin et al., (1990) mean^A (s.d.)	Difference^A [% Diff.]	Difference^D [% Diff.]	Female vs Male^B,C [%Diff.]
T8	1968 (606)	1582 (281)	386 [24]	283 [18]	1169 (461)				-799 [-41]
T9	1762 (437)	1417 (293)	345 [24]	201 [14]	1039 (501)				-723 [-41]
T10	1474 (448)	1239 (257)	235 [19]	192 [15]	895 (493)				-579 [-39]
T11	1388 (476)	1102 (316)	286 [26]	141 [13]	801 (428)				-587 [-42]
T12	1099 (405)	960 (310)	139 [14]	4 [0]	671 (390)				-428 [-39]
L1	829 (265)	682 (260)	147 [22]	32 [5]	531 (291)				-298 [-36]
L2	599 (237)	372 (161)	227 [61]	71 [19]	352 (245)	140 (60)	212 [151]	119 [85]	-247 [-41]
L3	287 (161)	256 (217)	31 [12]	-40 [-16]	165 (74)	130 (50)	35 [27]		-122 [-43]
L4	146 (11)					150 (60)			
L5									
S1									

A = Square mm;
B = Female minus Male (Square mm);
C = Shaded cells represent significant difference between females and males (p≤0.05);
D = Comparisons based on data adjusted one-half of a vertebral level.

Table 1.4. Mean (s.d.) trunk muscle cross-sectional area of the Right Erector Spinae. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of area and as a percent of the literature values [ ]. Absolute and percent differences in muscle areas between male and female subjects are also shown.

Right Erector Spinae - Cross-Sectional Area

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	Difference[D] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Difference[D] [% Diff.]	Female vs Male[B,C] [%Diff.]
T8	1287 (211)	1049 (201)	238 [23]	280 [27]	754 (161)				-533 [-41]
T9	1370 (249)	1413 (304)	-43 [-3]	30 [2]	830 (165)				-540 [-39]
T10	1516 (288)	1690 (210)	-174 [-10]	-71 [-4]	944 (182)				-572 [-38]
T11	1722 (284)	1832 (282)	-110 [-6]	-11 [-1]	1075 (244)				-647 [-38]
T12	1919 (285)	2614 (584)	-722 [-28]	-561 [-21]	1136 (244)				-783 [-41]
L1	2186 (345)	2615 (405)	-429 [-16]	-231 [-9]	1329 (324)				-857 [-39]
L2	2582 (420)	2854 (547)	-272 [-10]	-169 [-6]	1566 (384)	1820 (270)	-254 [-14]	-178 [-10]	-1016 [-39]
L3	2787 (417)	2831 (458)	-44 [2]	-70 [-3]	1718 (419)	1850 (300)	-132 [-7]	-149 [-8]	-1069 [-38]
L4	2735 (323)	2151 (539)	584 [27]	106 [5]	1683 (338)	1740 (300)	-57 [-3]	-403 [-23]	-1052 [-38]
L5	1779 (625)	905 (331)	874 [97]	392 [43]	991 (379)				-788 [-44]
S1	814 (162)				485 (124)				-329 [-40]

A = Square mm;
B = Female minus Male (Square mm);
C = Shaded cells represent significant difference between females and males (p≤0.05);
D = Comparisons based on data adjusted one-half of a vertebral level.

Table 1.5. Mean (s.d.) trunk muscle cross-sectional area of the Left Erector Spinae. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of area and as a percent of the literature values [ ]. Absolute and percent differences in muscle areas between male and female subjects are also shown.

Left Erector Spinae - Cross-Sectional Area

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	Difference[D] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Difference[D] [% Diff.]	Female vs Male[B,C] [%Diff.]
T8	1298 (223)	1129 (100)	169 [15]	212 [19]	773 (158)				-525 [-40]
T9	1384 (238)	1471 (351)	-87 [-6]	9 [1]	832 (185)				-552 [-40]
T10	1576 (303)	1722 (279)	-143 [-8]	-42 [-2]	958 (225)				-621 [-39]
T11	1783 (349)	2041 (285)	-258 [-13]	-181 [-9]	1072 (248)				-711 [-40]
T12	1937 (353)	2601 (559)	-664 [-26]	-540 [-21]	1143 (260)				-794 [-41]
L1	2184 (365)	2723 (428)	-539 [-20]	-356 [-13]	1319 (291)				-865 [-40]
L2	2549 (408)	2833 (456)	-284 [-10]	-164 [-6]	1542 (361)	1790 (310)	-248 [-14]	-153 [9]	-1007 [-40]
L3	2788 (447)	2933 (382)	-145 [-5]	-172 [-6]	1731 (363)	1850 (300)	-119 [-6]	-120 [-6]	-1057 [-38]
L4	2733 (376)	2234 (476)	499 [22]	50 [2]	1729 (329)	1730 (300)	-1 [0]	-387 [-22]	-1004 [-37]
L5	1834 (590)	986 (338)	848 [86]	358 [36]	956 (379)				-878 [-48]
S1	854 (165)				487 (137)				-367 [-43]

A = Square mm;
B = Female minus Male (Square mm);
C = Shaded cells represent significant difference between females and males (p≤0.05);
D = Comparisons based on data adjusted one-half of a vertebral level.

Table 1.6. Mean (s.d.) trunk muscle cross-sectional area of the Right Rectus Abdominis. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of area and as a percent of the literature values [ ]. Absolute and percent differences in muscle areas between male and female subjects are also shown.

Right Rectus Abdominis - Cross-Sectional Area

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	Difference[D] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Difference[D] [% Diff.]	Female vs Male[B,C] [%Diff.]
T8									
T9									
T10									
T11									
T12	489 (135)				367 (64)				-122 [-25]
L1	530 (130)	576 (151)	-46 [-8]	-65 [-11]	416 (108)				-114 [-22]
L2	492 (77)	712 (239)	-220 [-31]	-152 [-21]	354 (108)	330 (160)	24 [7]	43 [13]	-138 [-28]
L3	628 (231)	670 (133)	-42 [-6]	-15 [-2]	391 (116)	370 (110)	21 [6]	64 [18]	-237 [-38]
L4	682 (211)	750 (207)	-68 [-9]	0 [0]	480 (177)	400 (100)	80 [20]	79 [20]	-202 [-30]
L5	817 (204)	787 (250)	-30 [-4]	3 [0]	477 (129)				-340 [-42]
S1	761 (230)				454 (163)				-308 [-40]

A = Square mm;
B = Female minus Male (Square mm);
C = Shaded cells represent significant difference between females and males (p≤0.05);
D = Comparisons based on data adjusted one-half of spine level.

Table 1.7. Mean (s.d.) trunk muscle cross-sectional area of the Left Rectus Abdominis. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of area and as a percent of the literature values [ ]. Absolute and percent differences in muscle areas between male and female subjects are also shown.

Left Rectus Abdominis - Cross-Sectional Area

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	Difference[D] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Difference[D] [% Diff.]	Female vs Male[B,C] [%Diff.]
T8									
T9									
T10									
T11									
T12	530 (177)				405 (87)				-125 [-24]
L1	551 (174)	514 (99)	37 [7]	15 [3]	417 (100)				-134 [-24]
L2	506 (106)	748 (240)	-242 [-32]	-159 [-21]	363 (114)	340 (120)	23 [7]	40 [12]	-143 [-28]
L3	671 (234)	693 (177)	-22 [-3]	-28 [-4]	396 (116)	370 (120)	26 [7]	79 [20]	-275 [-41]
L4	659 (221)	746 (181)	-87 [-12]	4 [1]	495 (225)	410 (120)	85 [21]	81 [20]	-164 [-25]
L5	841 (237)	802 (247)	39 [5]	7 [1]	486 (122)				-355 [-42]
S1	776 (255)				451 (167)				-325 [-42]

A = Square mm;
B = Female minus Male (Square mm);
C = Shaded cells represent significant difference between females and males (p≤0.05);
D = Comparisons based on data adjusted one-half of spine level.

Table 1.8. Mean (s.d.) trunk muscle cross-sectional area of the Right External Obliques. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of area and as a percent of the literature values [ ]. Absolute and percent differences in muscle areas between male and female subjects are also shown.

Right External Obliques - Cross-Sectional Area

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	Difference[D] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Difference[D] [% Diff.]	Female vs Male[B,C] [%Diff.]
T8									
T9									
T10									
T11									
T12	533 (165)				429 (90)				-104 [-20]
L1	675 (175)				454 (101)				-221 [-33]
L2	710 (166)	1158 (222)	-448 [-39]	-333 [-29]	514 (125)	370 (120)	144 [39]	208 [56]	-196 [-28]
L3	940 (206)	1276 (171)	-336 [-26]	-251 [-20]	642 (119)	440 (140)	202 [46]	225 [51]	-298 [-32]
L4	1109 (220)	915 (199)	194 [21]	27 [3]	684 (113)	460 (140)	227 [49]	167 [36]	-422 [-38]
L5	775 (317)				567 (196)				-208 [-27]
S1					249 (-)				

A = Square mm;
B = Female minus Male (Square mm);
C = Shaded cells represent significant difference between females and males ($p \leq 0.05$);
D = Comparisons based on data adjusted one-half of spine level.

Table 1.9. Mean (s.d.) trunk muscle cross-sectional area of the Left External Obliques. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of area and as a percent of the literature values [ ]. Absolute and percent differences in muscle areas between male and female subjects are also shown.

Left External Obliques - Cross-Sectional Area

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	Difference[D] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Difference[D] [% Diff.]	Female vs Male[B,C] [%Diff.]
T8									
T9									
T10									
T11									
T12	503 (136)				384 (65)				-119 [-24]
L1	633 (150)				409 (83)				-224 [-35]
L2	706 (183)	1351 (282)	-645 [-48]	-537 [-40]	479 (95)	550 (160)	-71 [-13]	-6 [-1]	-227 [-32]
L3	921 (253)	1335 (213)	-414 [-31]	-315 [-24]	607 (118)	600 (140)	8 [1]	36 [6]	-313 [-34]
L4	1119 (238)	992 (278)	127 [13]	-11 [-1]	664 (104)	600 (160)	64 [11]	19 [3]	-455 [-41]
L5	843 (347)				574 (164)				-269 [-32]
S1					266 (-)				

A = Square mm;
B = Female minus Male (Square mm);
C = Shaded cells represent significant difference between females and males (p≤0.05);
D = Comparisons based on data adjusted one-half of spine level.

Table 1.10. Mean (s.d.) trunk muscle cross-sectional area of the Right Internal Obliques. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of area and as a percent of the literature values [ ]. Absolute and percent differences in muscle areas between male and female subjects are also shown.

Right Internal Obliques - Cross-Sectional Area

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	Difference[D] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Difference[D] [% Diff.]	Female vs Male[B,C] [%Diff.]
T8									
T9									
T10									
T11									
T12									
L1					127 (-)				
L2	234 (136)	1055 (173)	-821 [-78]	-613 [-58]	249 (165)	400 (140)	-151 [-38]	-84 [-21]	15 [6]
L3	650 (298)	1515 (317)	-865 [-57]	-680 [-45]	382 (200)	530 (130)	-148 [-28]	-53 [-10]	-268 [-41]
L4	1019 (255)	903 (83)	116 [13]	-98 [-11]	571 (170)	530 (180)	41 [8]	-34 [-6]	-448 [-44]
L5	591 (159)				421 (106)				-170 [-29]
S1					252 (-)				

A = Square mm;
B = Female minus Male (Square mm);
C = Shaded cells represent significant difference between females and males ($p \leq 0.05$);
D = Comparisons based on data adjusted one-half of spine level.

Table 1.11. Mean (s.d.) trunk muscle cross-sectional area of the Left Internal Obliques. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of area and as a percent of the literature values [ ]. Absolute and percent differences in muscle areas between male and female subjects are also shown.

Left Internal Obliques - Cross-Sectional Area

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	Difference[D] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Difference[D] [% Diff.]	Female vs Male[B,C] [%Diff.]
T8									
T9									
T10									
T11									
T12									
L1					94 (-)				
L2	298 (151)	1027 (342)	-729 [-71]	-547 [-53]	234 (139)	430 (150)	-196 [-46]	-132 [-31]	-64 [-21]
L3	661 (286)	1424 (310)	-763 [-54]	-568 [-40]	362 (193)	580 (150)	-218 [-38]	-110 [-19]	-299 [-45]
L4	1050 (274)	900 (115)	150 [17]	-59 [-7]	577 (137)	520 (150)	57 [11]	8 [1]	-473 [-45]
L5	632 (179)				478 (141)				-154 [-24]
S1					318 (-)				

A = Square mm;
B = Female minus Male (Square mm);
C = Shaded cells represent significant difference between females and males ($p \leq 0.05$);
D = Comparisons based on data adjusted one-half of spine level.

Table 1.12. Mean (s.d.) trunk muscle cross-sectional area of the Right Psoas Major. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of area and as a percent of the literature values [ ]. Absolute and percent differences in muscle areas between male and female subjects are also shown.

Right Psoas Major - Cross-Sectional Area

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	Difference[D] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Difference[D] [% Diff.]	Female vs Male[B,C] [%Diff.]
T8									
T9									
T10									
T11									
T12		330 (210)							
L1	261 (-)	513 (329)			193 (90)				
L2	694 (235)	1177 (285)	-483 [-41]	-173 [-15]	331 (83)	580 (150)	-249 [-43]	-85 [-15]	-363 [-52]
L3	1313 (302)	1594 (369)	-281 [-18]	-37 [-2]	658 (180)	830 (190)	-172 [-21]	-38 [-5]	-655 [-50]
L4	1801 (359)	1861 (347)	-60 [-3]	-122 [-7]	925 (164)	980 (200)	-55 [-6]	-101 [-10]	-876 [-49]
L5	1677 (381)	1606 (198)	71 [4]	-134 [-8]	832 (178)				-845 [-50]
S1	1266 (270)				648 (171)				-618 [-49]

A = Square mm;
B = Female minus Male (Square mm);
C = Shaded cells represent significant difference between females and males (p≤0.05);
D = Comparisons based on data adjusted one-half of spine level.

Table 1.13. Mean (s.d.) trunk muscle cross-sectional area of the Left Psoas Major. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of area and as a percent of the literature values [ ]. Absolute and percent differences in muscle areas between male and female subjects are also shown.

Left Psoas Major - Cross-Sectional Area

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	Difference[D] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Difference[D] [% Diff.]	Female vs Male[B,C] [%Diff.]
T8									
T9									
T10									
T11									
T12		462 (190)							
L1	322 (140)	488 (250)	-166 [-34]	71 [15]	202 (20)				-120 [-37]
L2	795 (253)	1211 (298)	-416 [-34]	-132 [-11]	347 (75)	590 (170)	-243 [-41]	-82 [-14]	-448 [-56]
L3	1362 (271)	1593 (291)	-231 [-15]	16 [1]	668 (167)	830 (190)	-162 [-20]	-8 [-1]	-694 [-51]
L4	1856 (306)	1820 (272)	36 [2]	-34 [-2]	975 (174)	980 (220)	-5 [-1]	-43 [-4]	-881 [-47]
L5	1716 (294)	1590 (244)	126 [8]	63 [4]	898 (172)				-818 [-48]
S1	1291 (281)				634 (174)				-657 [-51]

A = Square mm;
B = Female minus Male (Square mm);
C = Shaded cells represent significant difference between females and males (p≤0.05);
D = Comparisons based on data adjusted one-half of spine level.

Table 1.14. Mean (s.d.) trunk muscle cross-sectional area of the Right Quadratus Lumborum. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of area and as a percent of the literature values [ ]. Absolute and percent differences in muscle areas between male and female subjects are also shown.

Right Quadratus Lumborum - Cross-Sectional Area

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	Difference[D] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Difference[D] [% Diff.]	Female vs Male[B,C] [%Diff.]
T8									
T9									
T10									
T11									
T12		320 (197)							
L1	271 (-)	392 (249)	-121 [-31]	-98 [-25]	180 (56)				-91 [-34]
L2	316 (132)	552 (192)	-236 [-43]	-94 [-17]	196 (49)	300 (70)	-104 [-35]	-84 [-28]	-120 [-38]
L3	599 (215)	701 (212)	-102 [-15]	-63 [-9]	235 (57)	410 (120)	-175 [-43]	-112 [-27]	-364 [-61]
L4	677 (197)	725 (209)	-48 [-7]		361 (50)	460 (100)	-99 [-22]	-79 [-17]	-316 [-47]
L5					401 (-)				
S1									

A = Square mm;
B = Female minus Male (Square mm);
C = Shaded cells represent significant difference between females and males (p≤0.05);
D = Comparisons based on data adjusted one-half of spine level.

Table 1.15. Mean (s.d.) trunk muscle cross-sectional area of the Left Quadratus Lumborum. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of area and as a percent of the literature values [ ]. Absolute and percent differences in muscle areas between male and female subjects are also shown.

Left Quadratus Lumborum - Cross-Sectional Area

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	Difference[D] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Difference[D] [% Diff.]	Female vs Male[B,C] [%Diff.]
T8									
T9									
T10									
T11									
T12		326 (5)							
L1	285 (135)	404 (220)	-119 [-29]	-110 [-27]	173 (39)				-112 [-39]
L2	303 (120)	614 (189)	-311 [-51]	-283 [-25]	187 (48)	330 (160)	-143 [-43]	-102 [-31]	-116 [-38]
L3	623 (228)	746 (167)	-123 [-16]	-90 [-12]	269 (73)	450 (140)	-181 [-40]	-94 [-21]	-354 [-57]
L4	689 (196)	625 (249)	64 [10]		442 (83)	450 (130)	-8 [-2]	2 [0]	-247 [-36]
L5					461 (-)				
S1									

A = Square mm;
B = Female minus Male (Square mm);
C = Shaded cells represent significant difference between females and males (p≤0.05);
D = Comparisons based on data adjusted one-half of spine level.

Table 1.16. Vertebral body mean (s.d.) cross-sectional area. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of area and as a percent of the literature values [ ]. Absolute and percent differences in muscle areas between male and female subjects are also shown.

Vertebral Body - Cross-Sectional Area

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Female vs Male[B] [% Diff.]
T8	983 (181)	798 (91)	185 [23]	728 (107)			-255 [-26]
T9	1041 (205)	933 (112)	108 [12]	780 (90)			-261 [-25]
T10	1087 (166)	1015 (125)	72 [7]	843 (82)			-244 [-22]
T11	1225 (177)	1133 (124)	92 [8]	893 (97)			-332 [-27]
T12	1287 (189)	1241 (166)	46 [4]	937 (115)			-350 [-27]
L1	1249 (207)	1334 (285)	-85 [-6]	949 (95)			-300 [-24]
L2	1311 (240)	1332 (294)	-21 [-2]	1011 (115)	1420 (240)	-409 [-29]	-300 [-23]
L3	1413 (197)	1415 (249)	-2 [0]	1089 (114)	1520 (230)	-431 [-28]	-324 [-23]
L4	1478 (244)	1459 (270)	19 [1]	1125 (124)	1530 (220)	-405 [-26]	-353 [-24]
L5	1466 (222)	1360 (276)	106 [8]	1180 (219)			-286 [-20]
S1	1742 (261)			1275 (253)			-468 [-27]

A = Square mm
B = Female minus Male (Square mm)

Table 1.17. Trunk mass mean (s.d.) cross-sectional area. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of area and as a percent of the literature values [ ]. Absolute and percent differences in muscle areas between male and female subjects are also shown.

Trunk - Cross-Sectional Area

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Female vs Male[B] [% Diff.]
T8	73338 (11078)	65794 (5254)	7544 [11]	48230 (6569)			-25108 [-34]
T9	68831 (9016)	61732 (6960)	7099 [11]	46605 (6328)			-22226 [-32]
T10	64559 (8261)	61051 (7570)	3508 [6]	44405 (6122)			-20154 [-31]
T11	61648 (8553)	59249 (7272)	2399 [4]	43092 (5991)			-18556 [-30]
T12	59441 (8461)	63287 (9153)	-3846 [-6]	42551 (6003)			-16890 [-28]
L1	57478 (7934)	59091 (6899)	-1613 [-3]	41598 (6156)			-15880 [-28]
L2	54435 (8114)	55834 (8112)	-1399 [-3]	39913 (6135)	44300 (12200)	-4387 [-10]	-14522 [-27]
L3	52543 (8769)	54286 (8702)	-1743 [-3]	37756 (5791)	50900 (16800)	-13146 [-26]	-14789 [-28]
L4	51432 (10184)	51813 (9845)	-382 [-1]	38882 (7169)	57600 (15900)	-18718 [-33]	-12550 [-24]
L5	52481 (8823)	52912 (9123)	-431 [-1]	47166 (7766)			-5315 [-10]
S1	56547 (7701)			53320 (7958)			-3277 [-6]

A = Square mm
B = Female minus Male (Square mm)

Table 1.18. Right Latissimus Dorsi mean (s.d.) lateral moment-arm distance from the center of the vertebral body to the area centroid of the muscle cross-sectional area. Negative values represent right lateral and positive represent left lateral. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of the magnitude (mm) and as a percent of the literature values [ ]. Magnitude and percent difference in lateral moment-arms between male and female subjects are also shown.

Right Latissimus Dorsi - Corrected Lateral Moment Arms

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Female vs Male[B,C] [% Diff.]
T8	-153 (10)	-145 (7)	8 [4]	-132 (10)			-21 [-14]
T9	-145 (9)	-141 (8)	4 [3]	-124 (9)			-21 [-14]
T10	-135 (10)	-140 (9)	-5 [-4]	-114 (9)			-21 [-16]
T11	-128 (9)	-129 (9)	-1 [-1]	-109 (9)			-19 [-15]
T12	-122 (8)	-129 (10)	-7 [-5]	-104 (9)			-18 [-15]
L1	-116 (6)	-122 (12)	-6 [-5]	-99 (9)			-17 [-15]
L2	-109 (7)	-108 (8)	1 [1]	-93 (10)	-100 (11)	-7 [-7]	-16 [-15]
L3	-103 (8)	-102 (8)	1 [1]	-90 (11)	-106 (16)	-16 [-15]	-13 [-13]
L4	-110 (2)				-119 (11)		
L5							
S1							

A = millimeters (mm)
B = Female minus Male (mm)
C = Shaded cells represent significant difference between females and males ($p \leq 0.05$).

Table 1.19. Left Latissimus Dorsi mean (s.d.) lateral moment-arm distance from the center of the vertebral body to the area centroid of the muscle cross-sectional area. Negative values represent right lateral and positive represent left lateral. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of the magnitude (mm) and as a percent of the literature values [ ]. Magnitude and percent difference in lateral moment-arms between male and female subjects are also shown.

Left Latissimus Dorsi - Corrected Lateral Moment Arms

Level	OSU Male mean[A] (s. d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Female vs Male[B,C] [% Diff.]
T8	150 (7)	143 (6)	7 [5]	131 (9)			-19 [-13]
T9	140 (8)	139 (8)	1 [1]	122 (9)			-18 [-13]
T10	132 (9)	137 (9)	-5 [-4]	114 (10)			-18 [-14]
T11	126 (9)	129 (10)	-3 [-2]	108 (10)			-18 [-14]
T12	121 (9)	128 (7)	-7 [-5]	104 (9)			-17 [-14]
L1	116 (9)	117 (11)	-1 [-1]	101 (9)			-15 [-13]
L2	110 (7)	107 (9)	3 [3]	94 (11)	99 (12)	-5 [-5]	-16 [-15]
L3	105 (8)	104 (15)	1 [1]	92 (11)	107 (14)	-15 [-14]	-13 [-12]
L4	108 (8)				118 (15)		
L5							
S1							

A = millimeters (mm)
B = Female minus Male (mm)
C = Shaded cells represent significant difference between females and males (p≤0.05).

Table 1.20. Right Erector Spinae mean (s.d.) lateral moment-arm distance from the center of the vertebral body to the area centroid of the muscle cross-sectional area. Negative values represent right lateral and positive represent left lateral. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of the magnitude (mm) and as a percent of the literature values [ ]. Magnitude and percent difference in lateral moment-arms between male and female subjects are also shown.

Right Erector Spinae - Corrected Lateral Moment Arms

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Female vs Male[B,C] [% Diff.]
T8	-31 (2)	-31 (7)	0 [0]	-26 (3)			-5 [-16]
T9	-32 (3)	-32 (4)	0 [0]	-28 (3)			-4 [-13]
T10	-34 (3)	-34 (4)	0 [0]	-29 (3)			-5 [-15]
T11	-36 (3)	-34 (4)	2 [6]	-31 (3)			-5 [-14]
T12	-36 (3)	-42 (3)	-6 [-14]	-32 (3)			-4 [-11]
L1	-40 (4)	-44 (5)	-4 [-9]	-34 (3)			-6 [-15]
L2	-41 (3)	-42 (4)	-1 [-2]	-35 (3)	-34 (4)	1 [3]	-6 [-15]
L3	-38 (3)	-40 (4)	-2 [-5]	-34 (3)	-34 (4)	0 [0]	-4 [-11]
L4	-36 (3)	-34 (7)	2 [6]	-34 (3)	-35 (4)	-1 [3]	-2 [-6]
L5	-30 (7)	-22 (6)	8 [36]	-26 (6)			-4 [-13]
S1	-19 (3)			-19 (3)			-0 [-0]

A = millimeters (mm)
B = Female minus Male (mm)
C = Shaded cells represent significant difference between females and males ($p \leq 0.05$).

Table 1.21. Left Erector Spinae mean (s.d.) lateral moment-arm distance from the center of the vertebral body to the area centroid of the muscle cross-sectional area. Negative values represent right lateral and positive represent left lateral. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of the magnitude (mm) and as a percent of the literature values [ ]. Magnitude and percent difference in lateral moment-arms between male and female subjects are also shown.

Left Erector Spinae - Corrected Lateral Moment Arms

Level	OSU Male mean^{A} (s.d.)	McGill et al., (1993) mean^{A} (s.d.)	Difference^{A} [% Diff.]	OSU Female mean^{A} (s.d.)	Chaffin et al., (1990) mean^{A} (s.d.)	Difference^{A} [% Diff.]	Female vs Male^{B,C} [% Diff.]
T8	33 (4)	33 (6)	0 [0]	27 (4)			-6 [-18]
T9	34 (4)	35 (4)	-1 [-3]	28 (3)			-6 [-18]
T10	36 (3)	36 (3)	0 [0]	31 (2)			-5 [-14]
T11	38 (3)	40 (3)	-2 [-5]	32 (3)			-6 [-16]
T12	38 (3)	40 (4)	-2 [-5]	34 (4)			-4 [-11]
L1	42 (3)	41 (7)	1 [2]	35 (3)			-7 [-17]
L2	43 (4)	41 (6)	2 [5]	35 (3)	33 (4)	2 [6]	-8 [-19]
L3	40 (2)	38 (5)	2 [5]	35 (3)	34 (4)	1 [3]	-5 [-13]
L4	38 (3)	33 (6)	5 [15]	35 (3)	35 (4)	0 [0]	-3 [-8]
L5	32 (5)	21 (5)	11 [52]	27 (5)			-5 [-16]
S1	22 (2)			19 (2)			-3 [-14]

A = millimeters (mm)
B = Female minus Male (mm)
C = Shaded cells represent significant difference between females and males ($p \le 0.05$).

Table 1.22. Right Rectus Abdominis mean (s.d.) lateral moment-arm distance from the center of the vertebral body to the area centroid of the muscle cross-sectional area. Negative values represent right lateral and positive represent left lateral. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of the magnitude (mm) and as a percent of the literature values [ ]. Magnitude and percent difference in lateral moment-arms between male and female subjects are also shown.

Right Rectus Abdominis - Corrected Lateral Moment Arms

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Female vs Male[B,C] [% Diff.]
T8							
T9							
T10							
T11							
T12	-39 (6)			-29 (8)			-10 [-26]
L1	-46 (11)	-37 (8)	9 [24]	-34 (9)			-12 [-26]
L2	-49 (11)	-46 (8)	3 [7]	-36 (8)	-44 (12)	-8 [-18]	-13 [-27]
L3	-47 (7)	-43 (7)	4 [9]	-39 (8)	-43 (11)	-4 [-9]	-8 [-17]
L4	-46 (5)	-38 (7)	8 [21]	-40 (8)	-42 (11)	-2 [-5]	-6 [-13]
L5	-41 (5)	-32 (5)	9 [28]	-38 (9)			-3 [-7]
S1	-38 (5)			-33 (7)			-5 [-13]

A = millimeters (mm)
B = Female minus Male (mm)
C = Shaded cells represent significant difference between females and males ($p \leq 0.05$).

Table 1.23. Left Rectus Abdominis mean (s.d.) lateral moment-arm distance from the center of the vertebral body to the area centroid of the muscle cross-sectional area. Negative values represent right lateral and positive represent left lateral. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of the magnitude (mm) and as a percent of the literature values [ ]. Magnitude and percent difference in lateral moment-arms between male and female subjects are also shown.

Left Rectus Abdominis - Corrected Lateral Moment Arms

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Female vs Male[B,C] [% Diff.]
T8							
T9							
T10							
T11							
T12	35 (7)			35 (5)			0 [0]
L1	41 (8)	35 (17)	6 [17]	37 (7)			-4 [-10]
L2	39 (8)	43 (7)	-4 [-9]	34 (8)	42 (10)	-8 [-19]	-5 [-13]
L3	40 (7)	38 (8)	2 [5]	33 (9)	43 (12)	-10 [-23]	-7 [-18]
L4	36 (8)	36 (7)	0 [0]	35 (8)	41 (11)	-6 [-15]	-1 [-3]
L5	33 (8)	33 (5)	0 [0]	32 (8)			-1 [-3]
S1	29 (5)			33 (6)			4 [14]

A = millimeters (mm)
B = Female minus Male (mm)
C = Shaded cells represent significant difference between females and males (p≤0.05).

Table 1.24. Right External Obliques mean (s.d.) lateral moment-arm distance from the center of the vertebral body to the area centroid of the muscle cross-sectional area. Negative values represent right lateral and positive represent left lateral. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of the magnitude (mm) and as a percent of the literature values [ ]. Magnitude and percent difference in lateral moment-arms between male and female subjects are also shown.

Right External Obliques - Corrected Lateral Moment Arms

Level	OSU Male mean^A (s.d.)	McGill et al., (1993) mean^A (s.d.)	Difference^A [% Diff.]	OSU Female mean^A (s.d.)	Chaffin et al., (1990) mean^A (s.d.)	Difference^A [% Diff.]	Female vs Male^B,C [% Diff.]
T8							
T9							
T10							
T11							
T12	-129 (10)			-108 (8)			-21 [-16]
L1	-130 (12)			-109 (10)			-21 [-16]
L2	-132 (10)	-140 (5)	-8 [-6]	-109 (8)	-117 (15)	-8 [-7]	-21 [-16]
L3	-128 (7)	-130 (10)	-2 [-2]	-108 (7)	-120 (16)	-12 [-10]	-20 [-16]
L4	-128 (7)	-125 (13)	3 [2]	-112 (8)	-121 (14)	-9 [-7]	-16 [-13]
L5	-126 (6)			-116 (3)			-10 [-8]
S1				-106 (-)			

A = millimeters (mm)
B = Female minus Male (mm)
C = Shaded cells represent significant difference between females and males ($p \leq 0.05$).

Table 1.25. Left External Obliques mean (s.d.) lateral moment-arm distance from the center of the vertebral body to the area centroid of the muscle cross-sectional area. Negative values represent right lateral and positive represent left lateral. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of the magnitude (mm) and as a percent of the literature values [ ]. Magnitude and percent difference in lateral moment-arms between male and female subjects are also shown.

Left External Obliques - Corrected Lateral Moment Arms

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	OSU Fe male mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Female vs Male[B,C] [% Diff.]
T8							
T9							
T10							
T11							
T12	124 (9)			112 (10)			-12 [-10]
L1	126 (9)			110 (9)			-16 [-13]
L2	124 (11)	133 (7)	-9 [-7]	108 (10)	117 (14)	-9 [-8]	-16 [-13]
L3	124 (10)	125 (9)	-1 [-1]	106 (9)	122 (16)	-16 [-13]	-18 [-15]
L4	122 (9)	120 (9)	2 [2]	108 (9)	123 (20)	-15 [-12]	-14 [-11]
L5	125 (11)			113 (11)			-12 [-10]
S1				107 (-)			

A = millimeters (mm)
B = Female minus Male (mm)
C = Shaded cells represent significant difference between females and males (p≤0.05).

Table 1.26. Right Internal Obliques mean (s.d.) lateral moment-arm distance from the center of the vertebral body to the area centroid of the muscle cross-sectional area. Negative values represent right lateral and positive represent left lateral. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of the magnitude (mm) and as a percent of the literature values [ ]. Magnitude and percent difference in lateral moment-arms between male and female subjects are also shown.

Right Internal Obliques - Corrected Lateral Moment Arms

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Female vs Male[B,C] [% Diff.]
T8							
T9							
T10							
T11							
T12							
L1				-83 (-)			
L2	-114 (16)	-123 (9)	-9 [-2]	-99 (14)	-109 (15)	-10 [-9]	-15 [-13]
L3	-115 (8)	-116 (8)	-1 [-1]	-97 (11)	-113 (16)	-16 [-14]	-18 [-16]
L4	-114 (6)	-109 (11)	5 [5]	-101 (8)	-115 (20)	-14 [-12]	-13 [-11]
L5	-109 (3)			-104 (3)			-5 [-5]
S1				-92 (-)			

A = millimeters (mm)
B = Female minus Male (mm)
C = Shaded cells represent significant difference between females and males (p≤0.05).

Table 1.27. Left Internal Obliques mean (s.d.) lateral moment-arm distance from the center of the vertebral body to the area centroid of the muscle cross-sectional area. Negative values represent right lateral and positive represent left lateral. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of the magnitude (mm) and as a percent of the literature values [ ]. Magnitude and percent difference in lateral moment-arms between male and female subjects are also shown.

Left Internal Obliques - Corrected Lateral Moment Arms

Level	OSU Male mean^A (s.d.)	McGill et al., (1993) mean^A (s.d.)	Difference^A [% Diff.]	OSU Female mean^A (s.d.)	Chaffin et al., (1990) mean^A (s.d.)	Difference^A [% Diff.]	Female vs Male^B,C [% Diff.]
T8							
T9							
T10							
T11							
T12							
L1				93 (-)			
L2	107 (13)	121 (11)	-14 [-12]	102 (15)	109 (15)	-7 [-6]	-5 [-5]
L3	111 (14)	112 (8)	-1 [-1]	94 (14)	114 (16)	-20 [-18]	-17 [-15]
L4	107 (8)	103 (9)	4 [4]	98 (8)	114 (20)	-16 [-14]	-9 [-8]
L5	106 (9)			103 (10)			-3 [-3]
S1				94 (-)			

A = millimeters (mm)
B = Female minus Male (mm)
C = Shaded cells represent significant difference between females and males ($p \leq 0.05$).

Table 1.28. Right Psoas Major mean (s.d.) lateral moment-arm distance from the center of the vertebral body to the area centroid of the muscle cross-sectional area. Negative values represent right lateral and positive represent left lateral. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of the magnitude (mm) and as a percent of the literature values [ ]. Magnitude and percent difference in lateral moment-arms between male and female subjects are also shown.

Right Psoas Major - Corrected Lateral Moment Arms

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Female vs Male[B,C] [% Diff.]
T8							
T9							
T10							
T11							
T12		-32 (3)					
L1	-26 (-)	-32 (3)	-6 [-19]	-23 (2)			-3 [-12]
L2	-33 (3)	-39 (2)	-6 [-15]	-27 (2)	-33 (4)	-6 [-18]	-6 [-18]
L3	-39 (3)	-44 (3)	-5 [-11]	-33 (2)	-37 (4)	-4 [-11]	-6 [-15]
L4	-47 (3)	-50 (3)	-3 [-6]	-40 (3)	-44 (4)	-4 [-9]	-7 [-15]
L5	-53 (3)	-54 (4)	-1 [-2]	-47 (4)			-6 [-11]
S1	-56 (4)			-50 (4)			-6 [-11]

A = millimeters (mm)
B = Female minus Male (mm)
C = Shaded cells represent significant difference between females and males ($p \leq 0.05$).

Table 1.29. Left Psoas Major mean (s.d.) lateral moment-arm distance from the center of the vertebral body to the area centroid of the muscle cross-sectional area. Negative values represent right lateral and positive represent left lateral. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of the magnitude (mm) and as a percent of the literature values [ ]. Magnitude and percent difference in lateral moment-arms between male and female subjects are also shown.

Left Psoas Major - Corrected Lateral Moment Arms

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Female vs Male[B,C] [% Diff.]
T8							
T9							
T10							
T11							
T12		32 (2)					
L1	28 (2)	31 (3)	-3 [-10]	23 (1)			-5 [-18]
L2	33 (3)	38 (3)	-5 [-13]	27 (1)	32 (4)	-5 [-16]	-6 [-18]
L3	39 (3)	42 (3)	-3 [-7]	32 (2)	38 (4)	-5 [-13]	-7 [-18]
L4	44 (4)	48 (4)	-4 [-8]	38 (3)	43 (4)	-5 [-12]	-6 [-14]
L5	50 (5)	54 (5)	-4 [-7]	45 (3)			-5 [-10]
S1	54 (5)			51 (3)			-3 [-6]

A = millimeters (mm)
B = Female minus Male (mm)
C = Shaded cells represent significant difference between females and males ($p \leq 0.05$).

Table 1.30. Right Quadratus Lumborum mean (s.d.) lateral moment-arm distance from the center of the vertebral body to the area centroid of the muscle cross-sectional area. Negative values represent right lateral and positive represent left lateral. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of the magnitude (mm) and as a percent of the literature values [ ]. Magnitude and percent difference in lateral moment-arms between male and female subjects are also shown.

Right Quadratus Lumborum - Corrected Lateral Moment Arms

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Female vs Male[B,C] [% Diff.]
T8							
T9							
T10							
T11							
T12		-46 (11)					
L1	-38 (-)	-46 (6)	-8 [-17]	-38 (6)			0 [0]
L2	-50 (6)	-63 (5)	-13 [-21]	-41 (4)	-56 (8)	-15 [-27]	-9 [-18]
L3	-64 (6)	-75 (6)	-11 [-15]	-55 (7)	-65 (7)	-10 [-15]	-9 [-14]
L4	-75 (5)	-81 (5)	-6 [-7]	-68 (5)	-74 (8)	-6 [-8]	-7 [-9]
L5				-74 (-)			
S1							

A = millimeters (mm)
B = Female minus Male (mm)
C = Shaded cells represent significant difference between females and males (p≤0.05).

Table 1.31. Left Quadratus Lumborum mean (s.d.) lateral moment-arm distance from the center of the vertebral body to the area centroid of the muscle cross-sectional area. Negative values represent right lateral and positive represent left lateral. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of the magnitude (mm) and as a percent of the literature values [ ]. Magnitude and percent difference in lateral moment-arms between male and female subjects are also shown.

Left Quadratus Lumborum - Corrected Lateral Moment Arms

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Female vs Male[B,C] [% Diff.]
T8							
T9							
T10							
T11							
T12		47 (5)					
L1	44 (4)	50 (6)	-6 [-12]	37 (3)			-7 [-16]
L2	47 (10)	64 (5)	-17 [-27]	42 (3)	55 (7)	-13 [-24]	-5 [-11]
L3	65 (7)	73 (4)	-8 [-11]	57 (7)	65 (7)	-8 [-12]	-8 [-12]
L4	73 (6)	78 (12)	-5 [-6]	68 (7)	75 (10)	-7 [-9]	-5 [-7]
L5				79 (-)			
S1							

A = millimeters (mm)
B = Female minus Male (mm)
C = Shaded cells represent significant difference between females and males ($p \leq 0.05$).

Table 1.32. Right Latissimus Dorsi mean (s.d.) anterior-posterior moment-arm distance from the center of the vertebral body to the area centroid of the muscle cross-sectional area. Negative values represent right lateral and positive represent left lateral. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of the magnitude (mm) and as a percent of the literature values [ ]. Magnitude and percent difference in lateral moment-arms between male and female subjects are also shown.

Right Latissimus Dorsi - Corrected Anterior-Posterior Moment Arms

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Female vs Male[B,C] [% Diff.]
T8	-18 (9)	-18 (9)	0 [0]	-16 (12)			-2 [-11]
T9	-22 (10)	-22 (7)	0 [0]	-19 (11)			-3 [-14]
T10	-24 (9)	-24 (7)	0 [0]	-23 (9)			-1 [-4]
T11	-27 (8)	-32 (7)	-5 [-16]	-26 (8)			-1 [-4]
T12	-29 (7)	-39 (8)	-10 [-26]	-29 (8)			0 [0]
L1	-38 (9)	-47 (10)	-9 [-19]	-32 (10)			-6 [-16]
L2	-41 (7)	-47 (12)	-6 [-13]	-34 (11)	-36 (9)	-2 [-6]	-7 [-17]
L3	-42 (8)	-45 (16)	-3 [-7]	-31 (12)	-30 (10)	1 [3]	-11 [-26]
L4	-40 (13)				-17 (11)		
L5							
S1							

A = millimeters (mm)
B = Female minus Male (mm)
C = Shaded cells represent significant difference between females and males ($p \leq 0.05$).

Table 1.33. Left Latissimus Dorsi mean (s.d.) anterior-posterior moment-arm distance from the center of the vertebral body to the area centroid of the muscle cross-sectional area. Negative values represent right lateral and positive represent left lateral. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of the magnitude (mm) and as a percent of the literature values [ ]. Magnitude and percent difference in lateral moment-arms between male and female subjects are also shown.

Left Latissimus Dorsi - Corrected Anterior-Posterior Moment Arms

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Female vs Male[B,C] [% Diff.]
T8	-7 (11)	-17 (7)	-10 [-59]	-7 (10)			0 [0]
T9	-9 (11)	-19 (7)	-10 [-53]	-11 (9)			2 [22]
T10	-13 (11)	-23 (7)	-10 [-43]	-16 (9)			3 [23]
T11	-16 (10)	-28 (9)	-12 [-43]	-20 (8)			4 [25]
T12	-22 (10)	-37 (8)	-15 [-41]	-26 (8)			4 [18]
L1	-30 (12)	-46 (7)	-16 [-35]	-31 (10)			1 [3]
L2	-40 (11)	-46 (10)	-6 [-13]	-39 (11)	-34 (11)	5 [15]	-1 [-3]
L3	-39 (11)	-43 (17)	-4 [-9]	-40 (12)	-30 (10)	10 [33]	1 [3]
L4	-37 (11)				-14 (13)		
L5							
S1							

A = millimeters (mm)
B = Female minus Male (mm)
C = Shaded cells represent significant difference between females and males (p≤0.05).

Table 1.34. Right Erector Spinae mean (s.d.) anterior-posterior moment-arm distance from the center of the vertebral body to the area centroid of the muscle cross-sectional area. Negative values represent right lateral and positive represent left lateral. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of the magnitude (mm) and as a percent of the literature values [ ]. Magnitude and percent difference in lateral moment-arms between male and female subjects are also shown.

Right Erector Spinae - Corrected Anterior-Posterior Moment Arms

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Female vs Male[B,C] [% Diff.]
T8	-52 (4)	-52 (3)	0 [0]	-44 (3)			-8 [-15]
T9	-53 (4)	-52 (4)	1 [2]	-45 (4)			-8 [-15]
T10	-52 (4)	-54 (4)	-2 [-4]	-44 (4)			-8 [-15]
T11	-51 (4)	-54 (4)	-3 [-6]	-44 (4)			-7 [-14]
T12	-50 (4)	-56 (5)	-6 [-11]	-44 (4)			-6 [-12]
L1	-52 (5)	-59 (5)	-7 [-12]	-47 (5)			-5 [-10]
L2	-54 (7)	-61 (5)	-7 [-11]	-48 (4)	-54 (4)	-6 [-11]	-6 [-11]
L3	-57 (7)	-61 (5)	-4 [-7]	-50 (5)	-52 (4)	-2 [-4]	-7 [-12]
L4	-56 (6)	-61 (5)	-5 [-8]	-49 (4)	-52 (3)	-3 [-6]	-7 [-13]
L5	-61 (7)	-64 (6)	-3 [-5]	-54 (5)			-7 [-11]
S1	-62 (7)			-54 (5)			-8 [-13]

A = millimeters (mm)
B = Female minus Male (mm)
C = Shaded cells represent significant difference between females and males (p≤0.05).

Table 1.35. Left Erector Spinae mean (s.d.) anterior-posterior moment-arm distance from the center of the vertebral body to the area centroid of the muscle cross-sectional area. Negative values represent right lateral and positive represent left lateral. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of the magnitude (mm) and as a percent of the literature values [ ]. Magnitude and percent difference in lateral moment-arms between male and female subjects are also shown.

Left Erector Spinae - Corrected Anterior-Posterior Moment Arms

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Female vs Male[B,C] [% Diff.]
T8	-49 (5)	-51 (3)	-2 [-4]	-42 (3)			-7 [-14]
T9	-49 (6)	-51 (4)	-2 [-4]	-43 (3)			-6 [-12]
T10	-48 (5)	-52 (4)	-4 [-8]	-42 (3)			-6 [-13]
T11	-47 (5)	-52 (4)	-5 [-10]	-42 (4)			-5 [-11]
T12	-48 (5)	-57 (5)	-9 [-16]	-43 (4)			-5 [-10]
L1	-50 (6)	-60 (4)	-10 [-17]	-47 (5)			-3 [-6]
L2	-54 (6)	-62 (5)	-8 [-13]	-51 (6)	-54 (4)	-3 [-6]	-3 [-6]
L3	-56 (6)	-61 (5)	-5 [-8]	-53 (6)	-53 (2)	0 [0]	-3 [-5]
L4	-57 (5)	-61 (5)	-4 [-7]	-53 (5)	-54 (4)	-1 [-2]	-4 [-7]
L5	-61 (7)	-63 (5)	-2 [-3]	-57 (6)			-4 [-7]
S1	-63 (8)			-56 (5)			-7 [-11]

A = millimeters (mm)
B = Female minus Male (mm)
C = Shaded cells represent significant difference between females and males ($p \leq 0.05$).

Table 1.36. Right Rectus Abdominis mean (s.d.) anterior-posterior moment-arm distance from the center of the vertebral body to the area centroid of the muscle cross-sectional area. Negative values represent right lateral and positive represent left lateral. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of the magnitude (mm) and as a percent of the literature values [ ]. Magnitude and percent difference in lateral moment-arms between male and female subjects are also shown.

Right Rectus Abdominis - Corrected Anterior-Posterior Moment Arms

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Female vs. Male[B,C] [% Diff.]
T8							
T9							
T10							
T11							
T12	135 (17)			104 (9)			-31 [-23]
L1	124 (12)	109 (8)	15 [14]	96 (10)			-28 [-23]
L2	107 (12)	90 (14)	17 [19]	85 (9)	70 (15)	15 [21]	-24 [-22]
L3	89 (13)	79 (13)	10 [13]	70 (9)	70 (19)	0 [0]	-19 [-21]
L4	77 (15)	73 (14)	4 [5]	61 (9)	69 (20)	-8 [-12]	-16 [-21]
L5	76 (14)	81 (16)	-5 [-6]	65 (10)			-11 [-14]
S1	84 (12)			75 (13)			-9 [-11]

A = millimeters (mm)
B = Female minus Male (mm)
C = Shaded cells represent significant difference between females and males ($p \leq 0.05$).

Table 1.37. Left Rectus Abdominis mean (s.d.) anterior-posterior moment-arm distance from the center of the vertebral body to the area centroid of the muscle cross-sectional area. Negative values represent right lateral and positive represent left lateral. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of the magnitude (mm) and as a percent of the literature values [ ]. Magnitude and percent difference in lateral moment-arms between male and female subjects are also shown.

Left Rectus Abdominis - Corrected Anterior-Posterior Moment Arms

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Female vs. Male[B,C] [% Diff]
T8							
T9							
T10							
T11							
T12	137 (17)			105 (10)			-32 [-23]
L1	127 (11)	112 (6)	15 [13]	97 (11)			-30 [-24]
L2	108 (13)	92 (14)	16 [17]	85 (11)	72 (16)	13 [18]	-23 [-21]
L3	92 (13)	80 (14)	12 [15]	69 (11)	72 (19)	-3 [-4]	-23 [-25]
L4	78 (14)	73 (14)	5 [7]	60 (9)	70 (20)	-10 [-14]	-18 [-23]
L5	76 (15)	80 (15)	-4 [-5]	61 (10)			-15 [-20]
S1	82 (12)			73 (12)			-9 [-11]

A = millimeters (mm)
B = Female minus Male (mm)
C = Shaded cells represent significant difference between females and males (p≤0.05).

Table 1.38. Right External Obliques mean (s.d.) anterior-posterior moment-arm distance from the center of the vertebral body to the area centroid of the muscle cross-sectional area. Negative values represent right lateral and positive represent left lateral. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of the magnitude (mm) and as a percent of the literature values [ ]. Magnitude and percent difference in lateral moment-arms between male and female subjects are also shown.

Right External Obliques - Corrected Anterior-Posterior Moment Arms

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Female vs Male[B,C] [% Diff.]
T8							
T9							
T10							
T11							
T12	85 (12)			68 (7)			-17 [-20]
L1	67 (10)			56 (12)			-11 [-16]
L2	46 (6)	28 (12)	18 [64]	40 (11)	22 (13)	18 [82]	-6 [-13]
L3	22 (10)	20 (14)	2 [10]	24 (12)	23 (12)	1 [4]	2 [9]
L4	21 (8)	35 (10)	-14 [-40]	22 (12)	30 (13)	-8 [-27]	1 [5]
L5	39 (12)			32 (20)			-7 [-18]
S1				66 (-)			

A = millimeters (mm)
B = Female minus Male (mm)
C = Shaded cells represent significant difference between females and males (p≤0.05).

Table 1.39. Left External Obliques mean (s.d.) anterior-posterior moment-arm distance from the center of the vertebral body to the area centroid of the muscle cross-sectional area. Negative values represent right lateral and positive represent left lateral. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of the magnitude (mm) and as a percent of the literature values [ ]. Magnitude and percent difference in lateral moment-arms between male and female subjects are also shown.

Left External Obliques - Corrected Anterior-Posterior Moment Arms

Level	OSU Male mean^A (s.d.)	McGill et al., (1993) mean^A (s.d.)	Difference^A [% Diff.]	OSU Female mean^A (s.d.)	Chaffin et al., (1990) mean^A (s.d.)	Difference^A [% Diff.]	Female vs Male^B,C [% Diff.]
T8							
T9							
T10							
T11							
T12	92 (14)			66 (12)			-26 [-28]
L1	74 (13)			57 (13)			-17 [-23]
L2	50 (14)	28 (11)	22 [79]	37 (12)	20 (11)	17 [85]	-13 [-26]
L3	27 (14)	19 (11)	8 [42]	15 (13)	20 (11)	-5 [-25]	-12 [-44]
L4	20 (11)	32 (18)	-12 [-38]	12 (13)	30 (12)	-18 [-60]	-8 [-40]
L5	35 (12)			25 (9)			-10 [-29]
S1				46 (-)			

A = millimeters (mm)
B = Female minus Male (mm)
C = Shaded cells represent significant difference between females and males ($p \leq 0.05$).

Table 1.40. Right Internal Obliques mean (s.d.) anterior-posterior moment-arm distance from the center of the vertebral body to the area centroid of the muscle cross-sectional area. Negative values represent right lateral and positive represent left lateral. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of the magnitude (mm) and as a percent of the literature values [ ]. Magnitude and percent difference in lateral moment-arms between male and female subjects are also shown.

Right Internal Obliques - Corrected Anterior-Posterior Moment Arms

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Female vs Male[B,C] [% Diff.]
T8							
T9							
T10							
T11							
T12							
L1				93 (-)			
L2	72 (17)	36 (17)	36 [100]	55 (15)	24 (14)	31 [129]	-17 [-24]
L3	34 (13)	25 (9)	9 [36]	33 (12)	21 (11)	12 [57]	-1 [-3]
L4	25 (11)	41 (12)	-16 [-39]	21 (11)	30 (15)	-9 [-30]	-4 [-16]
L5	45 (10)			36 (15)			-9 [-20]
S1				63 (-)			

A = millimeters (mm)
B = Female minus Male (mm)
C = Shaded cells represent significant difference between females and males ($p \leq 0.05$).

Table 1.41. Left Internal Obliques mean (s.d.) anterior-posterior moment-arm distance from the center of the vertebral body to the area centroid of the muscle cross-sectional area. Negative values represent right lateral and positive represent left lateral. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of the magnitude (mm) and as a percent of the literature values [ ]. Magnitude and percent difference in lateral moment-arms between male and female subjects are also shown.

Left Internal Obliques - Corrected Anterior-Posterior Moment Arms

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Female vs Male[B,C] [% Diff.]
T8							
T9							
T10							
T11							
T12							
L1				78 (-)			
L2	77 (16)	40 (16)	37 [93]	50 (19)	25 (16)	25 [100]	-27 [-35]
L3	43 (15)	26 (12)	17 [65]	30 (15)	20 (10)	10 [50]	-13 [-30]
L4	27 (10)	41 (17)	-14 [-34]	16 (10)	28 (13)	-12 [-43]	-11 [-41]
L5	45 (13)			30 (15)			-15 [-33]
S1				44 (-)			

A = millimeters (mm)
B = Female minus Male (mm)
C = Shaded cells represent significant difference between females and males ($p \leq 0.05$).

Table 1.42. Right Psoas Major mean (s.d.) anterior-posterior moment-arm distance from the center of the vertebral body to the area centroid of the muscle cross-sectional area. Negative values represent right lateral and positive represent left lateral. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of the magnitude (mm) and as a percent of the literature values [ ]. Magnitude and percent difference in lateral moment-arms between male and female subjects are also shown.

Right Psoas Major - Corrected Anterior-Posterior Moment Arms

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Female vs Male[B,C] [% Diff.]
T8							
T9							
T10							
T11							
T12		-14 (2)					
L1	-5 (-)	-11 (6)	-6 [-55]	-7 (9)			2 [40]
L2	-7 (5)	-9 (5)	-2 [-22]	-9 (3)	-11 (3)	-2 [-18]	2 [29]
L3	-4 (4)	-7 (5)	-3 [-43]	-8 (4)	-8 (4)	0 [0]	4 [100]
L4	-1 (3)	1 (5)	-2 [-200]	-4 (5)	-2 (5)	2 [100]	3 [300]
L5	8 (5)	18 (9)	-10 [-56]	7 (7)			-1 [-13]
S1	24 (7)			23 (10)			-1 [-4]

A = millimeters (mm)
B = Female minus Male (mm)
C = Shaded cells represent significant difference between females and males (p≤0.05).

Table 1.43. Left Psoas Major mean (s.d.) anterior-posterior moment-arm distance from the center of the vertebral body to the area centroid of the muscle cross-sectional area. Negative values represent right lateral and positive represent left lateral. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of the magnitude (mm) and as a percent of the literature values [ ]. Magnitude and percent difference in lateral moment-arms between male and female subjects are also shown.

Left Psoas Major - Corrected Anterior-Posterior Moment Arms

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Female vs Male[B,C] [% Diff.]
T8							
T9							
T10							
T11							
T12		-11 (1)					
L1	-9 (5)	-11 (4)	-2 [-18]	-2 (7)			-7 [-22]
L2	-6 (5)	-8 (2)	-2 [-25]	-10 (4)	-11 (4)	-1 [-9]	4 [67]
L3	-3 (4)	-6 (4)	-3 [-50]	-10 (5)	-8 (5)	2 [25]	7 [233]
L4	-0.2 (5)	2 (4)	-2.2 [-110]	-7 (5)	-2 (4)	5 [250]	7.2 [3600]
L5	8 (6)	19 (8)	-11 [-58]	2 (6)			-6 [-75]
S1	24 (7)			20 (8)			-4 [-17]

A = millimeters (mm)
B = Female minus Male (mm)
C = Shaded cells represent significant difference between females and males ($p \leq 0.05$).

Table 1.44. Right Quadratus Lumborum mean (s.d.) anterior-posterior moment-arm distance from the center of the vertebral body to the area centroid of the muscle cross-sectional area. Negative values represent right lateral and positive represent left lateral. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of the magnitude (mm) and as a percent of the literature values [ ]. Magnitude and percent difference in lateral moment-arms between male and female subjects are also shown.

Right Quadratus Lumborum - Corrected Anterior-Posterior Moment Arms

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Female vs Male[B,C] [% Diff.]
T8							
T9							
T10							
T11							
T12		-31 (6)					
L1	-27 (-)	-35 (4)	-8 [-23]	-29 (4)			2 [7]
L2	-31 (6)	-37 (6)	-6 [-16]	-30 (4)	-36 (4)	-6 [-17]	-1 [-3]
L3	-31 (7)	-37 (6)	-6 [-16]	-31 (7)	-32 (7)	-1 [-3]	0 [0]
L4	-30 (6)	-36 (9)	-6 [-17]	-26 (8)	-28 (7)	-2 [-7]	-4 [-13]
L5				-18 (-)			
S1							

A = millimeters (mm)
B = Female minus Male (mm)
C = Shaded cells represent significant difference between females and males ($p \leq 0.05$).

Table 1.45. Left Quadratus Lumborum mean (s.d.) anterior-posterior moment-arm distance from the center of the vertebral body to the area centroid of the muscle cross-sectional area. Negative values represent right lateral and positive represent left lateral. Data collected (OSU) are compared with literature values for males and females. Differences between literature values and the current data are described in terms of the magnitude (mm) and as a percent of the literature values [ ]. Magnitude and percent difference in lateral moment-arms between male and female subjects are also shown.

Left Quadratus Lumborum - Corrected Anterior-Posterior Moment Arms

Level	OSU Male mean[A] (s.d.)	McGill et al., (1993) mean[A] (s.d.)	Difference[A] [% Diff.]	OSU Female mean[A] (s.d.)	Chaffin et al., (1990) mean[A] (s.d.)	Difference[A] [% Diff.]	Female vs Male[B,C] [% Diff.]
T8							
T9							
T10							
T11							
T12		-31 (6)					
L1	-30 (4)	-35 (4)	-5 [-14]	-26 (3)			-4 [-13]
L2	-31 (6)	-37 (6)	-6 [-16]	-32 (6)	-36 (4)	-4 [-11]	1 [3]
L3	-31 (7)	-37 (6)	-6 [-16]	-36 (10)	-32 (7)	4 [13]	5 [16]
L4	-31 (7)	-36 (9)	-5 [-14]	-32 (10)	-28 (7)	4 [14]	1 [3]
L5				-29 (-)			
S1							

A = millimeters (mm)
B = Female minus Male (mm)
C = Shaded cells represent significant difference between females and males (p≤0.05).

Table 1.46. Right Latissimus Dorsi mean (s.d.) muscle vector directions (degrees) in the lateral (θ_{Lat}) and anterior-posterior (θ_{Sag}) planes. Negative values represent right lateral or posterior direction, and positive values represent left lateral or anterior direction. Differences between the male and female vector directions are shown, which are the absolute difference in degrees. Significant differences between males and females are indicated when p≤0.05.

Right Latissimus Dorsi - Muscle Vector Directions (degrees) in the Anterior-Posterior and Lateral Planes

Level	Female θ_{Lat} mean[A] (s.d.)	Male θ_{Lat} mean[A] (s.d.)	Difference[B]	Female θ_{Sag} mean[A] (s.d.)	Male θ_{Sag} mean[A] (s.d.)	Difference[B]
T8	-18.4 (5.5)	-16.7 (9.0)	1.7	10.3 (10.6)	9.7 (10.0)	0.6
T9	-20.6 (6.8)	-15.2 (16.0)	5.4	14.5 (11.6)	11.2 (11.5)	3.3
T10	-10.9 (7.6)	-13.5 (7.9)	2.6	15.5 (11.4)	8.9 (12.5)	6.6
T11	-10.8 (5.6)	-11.8 (4.3)	1.0	14.6 (8.8)	11.6 (9.0)	3.0
T12	-8.9 (11.6)	-9.7 (4.9)	0.8	18.2 (7.7)	23.5 (14.5)	5.3
L1	-11.8 (14.9)	-11.4 (8.2)	0.4	18.1 (12.9)	17.2 (7.6)	0.9
L2	-3.6 (14.2)	-9.0 (9.2)	5.4	11.4 (12.4)	12.6 (9.0)	1.2
L3		8.3 (0.4)			-0.2 (0.8)	
L4						
L5						

A = Degrees
B = Shaded cells represent significant difference between females and males.

Table 1.47. Left Latissimus Dorsi mean (s.d.) muscle vector directions (degrees) in the lateral (θ_{Lat}) and anterior-posterior (θ_{Sag}) planes. Negative values represent right lateral or posterior direction, and positive values represent left lateral or anterior direction. Differences between the male and female vector directions are shown, which are the absolute difference in degrees. Significant differences between males and females are indicated when p≤0.05.

Left Latissimus Dorsi - Muscle Vector Directions (degrees) in the Anterior-Posterior and Lateral Planes

Level	Female θ_{Lat} mean[A] (s.d.)	Male θ_{Lat} mean[A] (s.d.)	Difference[B]	Female θ_{Sag} mean[A] (s.d.)	Male θ_{Sag} mean[A] (s.d.)	Difference[B]
T8	19.3 (7.6)	20.7 (10.5)	1.4	14.7 (9.7)	6.2 (8.7)	8.5
T9	20.9 (6.8)	21.3 (7.1)	0.4	16.1 (7.1)	15.0 (10.6)	0.9
T10	12.4 (7.5)	11.5 (6.1)	0.9	16.1 (11.9)	9.2 (16.8)	6.9
T11	8.6 (6.1)	9.7 (6.8)	1.1	21.3 (9.5)	17.4 (6.2)	3.9
T12	5.3 (12.2)	8.7 (6.5)	3.4	20.4 (13.4)	23.4 (12.5)	3.0
L1	9.8 (15.6)	9.1 (7.8)	0.7	26.3 (11.3)	25.6 (9.8)	0.7
L2	0.5 (14.4)	9.0 (9.2)	8.5	15.6 (9.2)	10.6 (7.6)	5.0
L3		-5.5 (3.1)			7.3 (2.0)	
L4						
L5						

A = Degrees
B = Shaded cells represent significant difference between females and males.

Table 1.48. Right Erector Spinae mean (s.d.) muscle vector directions (degrees) in the lateral (θ_{Lat}) and anterior-posterior (θ_{Sag}) planes. Negative values represent right lateral or posterior direction, and positive values represent left lateral or anterior direction. Differences between the male and female vector directions are shown, which are the absolute difference in degrees. Significant differences between males and females are indicated when $p \leq 0.05$.

Right Erector Spinae - Muscle Vector Directions (degrees) in the Anterior-Posterior and Lateral Planes

Level	Female θ_{Lat} mean[A] (s.d.)	Male θ_{Lat} mean[A] (s.d.)	Difference[B]	Female θ_{Sag} mean[A] (s.d.)	Male θ_{Sag} mean[A] (s.d.)	Difference[B]
T8	3.1 (5.1)	3.5 (4.9)	0.4	5.7 (5.6)	3.9 (4.3)	1.9
T9	5.2 (4.5)	7.7 (11.2)	2.5	5.6 (6.0)	5.1 (11.3)	0.6
T10	4.6 (3.8)	4.3 (4.8)	0.3	8.3 (7.2)	2.3 (5.0)	6.0
T11	0.8 (5.9)	0.4 (3.5)	0.4	9.6 (4.2)	4.2 (5.3)	5.4
T12	4.0 (3.6)	7.1 (6.1)	3.1	16.4 (5.3)	15.2 (9.3)	1.2
L1	0.2 (6.5)	1.0 (4.2)	0.8	17.9 (6.2)	14.7 (9.2)	3.2
L2	-2.8 (4.9)	-2.7 (3.8)	0.1	15.7 (6.5)	15.0 (2.9)	0.7
L3	1.8 (4.2)	-3.7 (4.0)	5.5	8.0 (5.5)	8.2 (3.4)	0.2
L4	-11.0 (10.2)	-7.6 (8.0)	3.4	4.3 (9.5)	7.7 (4.9)	3.3
L5	-10.3 (13.0)	-17.7 (7.0)	7.4	-20.5 (16.6)	-12.9 (6.5)	7.6

A = Degrees
B = Shaded cells represent significant difference between females and males.

Table 1.49. Left Erector Spinae mean (s.d.) muscle vector directions (degrees) in the lateral (θ_{Lat}) and anterior-posterior (θ_{Sag}) planes. Negative values represent right lateral or posterior direction, and positive values represent left lateral or anterior direction. Differences between the male and female vector directions are shown, which are the absolute difference in degrees. Significant differences between males and females are indicated when p≤0.05.

Left Erector Spinae - Muscle Vector Directions (degrees) in the Anterior-Posterior and Lateral Planes

Level	Female θ_{Lat} mean[A] (s.d.)	Male θ_{Lat} mean[A] (s.d.)	Difference[B]	Female θ_{Sag} mean[A] (s.d.)	Male θ_{Sag} mean[A] (s.d.)	Difference[B]
T8	-5.0 (6.5)	-2.5 (6.6)	2.5	6.4 (5.3)	2.8 (4.5)	3.6
T9	-4.6 (6.8)	-0.1 (11.4)	4.5	4.9 (5.4)	6.4 (11.0)	2.5
T10	-2.3 (6.0)	-1.8 (5.3)	0.5	7.5 (7.1)	1.9 (5.3)	5.6
T11	-3.2 (4.3)	-0.4 (3.2)	2.8	12.4 (5.5)	6.7 (6.2)	5.7
T12	-4.4 (5.8)	-7.3 (2.9)	2.8	19.3 (7.0)	15.1 (8.8)	4.1
L1	-1.3 (4.1)	-1.9 (3.2)	0.6	21.2 (5.6)	17.5 (7.6)	3.7
L2	-0.3 (3.7)	5.7 (4.6)	6.0	17.6 (5.5)	14.4 (3.2)	3.3
L3	1.4 (3.5)	3.6 (3.6)	2.2	7.4 (4.7)	11.3 (3.4)	3.9
L4	13.9 (10.4)	10.7 (7.2)	3.2	3.7 (9.4)	6.2 (5.6)	2.5
L5	21.5 (8.7)	20.0 (9.1)	1.5	-23.6 (16.8)	-11.3 (9.3)	12.3

A = Degrees
B = Shaded cells represent significant difference between females and males.

Table 1.50. Right Rectus Abdominis mean (s.d.) muscle vector directions (degrees) in the lateral (θ_{Lat}) and anterior-posterior (θ_{Sag}) planes. Negative values represent right lateral or posterior direction, and positive values represent left lateral or anterior direction. Differences between the male and female vector directions are shown, which are the absolute difference in degrees. Significant differences between males and females are indicated when p≤0.05.

Right Rectus Abdominis - Muscle Vector Directions (degrees) in the Anterior-Posterior and Lateral Planes

Level	Female θ_{Lat} mean[A] (s.d.)	Male θ_{Lat} mean[A] (s.d.)	Difference[B]	Female θ_{Sag} mean[A] (s.d.)	Male θ_{Sag} mean[A] (s.d.)	Difference[B]
T8						
T9						
T10						
T11						
T12	10.4 (13.0)	10.9 (5.8)	0.5	26.1 (5.5)	26.9 (14.5)	0.8
L1	3.9 (11.1)	3.8 (13.4)	0.1	32.0 (9.3)	33.5 (9.9)	1.5
L2	3.5 (7.3)	-2.0 (6.8)	5.5	33.8 (5.7)	34.9 (4.9)	1.1
L3	2.6 (7.6)	0.0 (5.9)	2.6	21.6 (8.7)	25.5 (7.5)	3.9
L4	-0.2 (9.2)	-5.9 (4.2)	5.7	-9.0 (14.4)	3.2 (11.4)	12.2
L5	-8.0 (8.7)	-3.2 (6.2)	4.8	-37.4 (14.0)	-28.7 (12.5)	8.7

A = Degrees
B = Shaded cells represent significant difference between females and males.

Table 1.51. Left Rectus Abdominis mean (s.d.) muscle vector directions (degrees) in the lateral (θ_{Lat}) and anterior-posterior (θ_{Sag}) planes. Negative values represent right lateral or posterior direction, and positive values represent left lateral or anterior direction. Differences between the male and female vector directions are shown, which are the absolute difference in degrees. Significant differences between males and females are indicated when p≤0.05.

Left Rectus Abdominis - Muscle Vector Directions (degrees) in the Anterior-Posterior and Lateral Planes

Level	Female θ_{Lat} mean[A] (s.d.)	Male θ_{Lat} mean[A] (s.d.)	Difference[B]	Female θ_{Sag} mean[A] (s.d.)	Male θ_{Sag} mean[A] (s.d.)	Difference[B]
T8						
T9						
T10						
T11						
T12	1.6 (8.9)	-9.1 (12.5)	10.7	26.0 (5.1)	25.4 (13.0)	0.6
L1	3.1 (9.6)	1.4 (11.7)	1.7	33.7 (8.5)	36.5 (7.3)	2.7
L2	0.5 (7.8)	0.6 (4.9)	0.1	35.5 (5.7)	33.0 (4.8)	2.5
L3	-1.9 (5.7)	6.6 (7.0)	8.5	22.3 (8.6)	27.7 (7.7)	5.4
L4	6.4 (6.6)	6.8 (5.8)	0.4	-6.1 (14.0)	3.8 (10.0)	9.9
L5	4.1 (8.3)	9.5 (4.2)	5.4	-39.7 (13.8)	-25.7 (14.3)	14.0

A = Degrees
B = Shaded cells represent significant difference between females and males.

Table 1.52. Right External Obliques mean (s.d.) muscle vector directions (degrees) in the lateral (θ_{Lat}) and anterior-posterior (θ_{Sag}) planes. Negative values represent right lateral or posterior direction, and positive values represent left lateral or anterior direction. Differences between the male and female vector directions are shown, which are the absolute difference in degrees. Significant differences between males and females are indicated when p≤0.05.

Right External Obliques - Muscle Vector Directions (degrees) in the Anterior-Posterior and Lateral Planes

Level	Female θ_{Lat} mean[A] (s.d.)	Male θ_{Lat} mean[A] (s.d.)	Difference[B]	Female θ_{Sag} mean[A] (s.d.)	Male θ_{Sag} mean[A] (s.d.)	Difference[B]
T8						
T9						
T10						
T11						
T12	4.1 (9.3)	5.0 (6.2)	0.9	27.2 (6.2)	37.1 (11.5)	9.9
L1	-0.4 (10.5)	2.9 (5.4)	3.3	36.4 (8.8)	39.0 (6.3)	2.6
L2	-3.3 (5.7)	-5.0 (5.5)	1.7	35.9 (6.8)	40.1 (7.1)	4.2
L3	6.2 (8.2)	-0.1 (4.4)	6.4	11.8 (17.9)	10.2 (7.7)	1.6
L4	6.4 (5.8)	-0.7 (8.3)	7.1	-27.0 (15.8)	-19.8 (14.0)	7.2
L5	-7.9 (-)			-56.7 (-)		

A = Degrees
B = Shaded cells represent significant difference between females and males.

Table 1.53. Left External Obliques mean (s.d.) muscle vector directions (degrees) in the lateral (θ_{Lat}) and anterior-posterior (θ_{Sag}) planes. Negative values represent right lateral or posterior direction, and positive values represent left lateral or anterior direction. Differences between the male and female vector directions are shown, which are the absolute difference in degrees. Significant differences between males and females are indicated when p≤0.05.

Left External Obliques - Muscle Vector Directions (degrees) in the Anterior-Posterior and Lateral Planes

Level	Female θ_{Lat} mean[A] (s.d.)	Male θ_{Lat} mean[A] (s.d.)	Difference[B]	Female θ_{Sag} mean[A] (s.d.)	Male θ_{Sag} mean[A] (s.d.)	Difference[B]
T8						
T9						
T10						
T11						
T12	5.8 (7.9)	-4.8 (10.5)	10.5	31.6 (5.6)	35.9 (11.9)	4.3
L1	2.2 (8.9)	2.2 (4.6)	0.0	41.0 (10.3)	41.0 (8.6)	0.0
L2	2.9 (4.2)	1.8 (2.7)	1.1	40.9 (4.9)	39.8 (8.5)	1.1
L3	-3.7 (4.6)	3.0 (5.1)	6.7	13.8 (13.1)	18.6 (11.2)	4.8
L4	-0.3 (6.0)	-0.7 (6.1)	0.4	-22.0 (13.0)	-19.3 (11.2)	2.7
L5	16.0 (-)			-52.7 (-)		

A = Degrees
B = Shaded cells represent significant difference between females and males.

Table 1.54. Right Internal Obliques mean (s.d.) muscle vector directions (degrees) in the lateral (θ_{Lat}) and anterior-posterior (θ_{Sag}) planes. Negative values represent right lateral or posterior direction, and positive values represent left lateral or anterior direction. Differences between the male and female vector directions are shown, which are the absolute difference in degrees. Significant differences between males and females are indicated when p≤0.05.

Right Internal Obliques - Muscle Vector Directions (degrees) in the Anterior-Posterior and Lateral Planes

Level	Female θ_{Lat} mean[A] (s.d.)	Male θ_{Lat} mean[A] (s.d.)	Difference[B]	Female θ_{Sag} mean[A] (s.d.)	Male θ_{Sag} mean[A] (s.d.)	Difference[B]
T8						
T9						
T10						
T11						
T12						
L1	22.6 (-)			48.7 (-)		
L2	7.8 (13.9)	5.9 (15.5)	1.9	45.7 (12.0)	51.3 (10.2)	5.6
L3	6.5 (11.7)	-2.0 (8.8)	8.5	24.7 (21.0)	20.6 (18.9)	4.2
L4	6.4 (9.2)	-7.9 (8.5)	14.3	-27.5 (6.5)	-27.2 (6.0)	0.3
L5	-17.3 (-)			-54.4 (-)		

A = Degrees
B = Shaded cells represent significant difference between females and males.

Table 1.55. Left Internal Obliques mean (s.d.) muscle vector directions (degrees) in the lateral (θ_{Lat}) and anterior-posterior (θ_{Sag}) planes. Negative values represent right lateral or posterior direction, and positive values represent left lateral or anterior direction. Differences between the male and female vector directions are shown, which are the absolute difference in degrees. Significant differences between males and females are indicated when p≤0.05.

Left Internal Obliques - Muscle Vector Directions (degrees) in the Anterior-Posterior and Lateral Planes

Level	Female θ_{Lat} mean[A] (s.d.)	Male θ_{Lat} mean[A] (s.d.)	Difference[B]	Female θ_{Sag} mean[A] (s.d.)	Male θ_{Sag} mean[A] (s.d.)	Difference[B]
T8						
T9						
T10						
T11						
T12						
L1	-12.1 (-)			53.4 (-)		
L2	-2.3 (13.0)	-5.5 (9.3)	3.2	44.1 (9.9)	45.4 (8.5)	1.3
L3	-6.5 (11.0)	4.5 (11.3)	11.0	27.3 (18.9)	27.5 (16.3)	0.2
L4	0.6 (2.2)	6.2 (7.8)	5.6	-21.5 (6.4)	-22.8 (10.1)	1.3
L5	25.7 (-)			-49.6 (-)		

A = Degrees
B = Shaded cells represent significant difference between females and males.

Table 1.56. Right Psoas Major mean (s.d.) muscle vector directions (degrees) in the lateral (θ_{Lat}) and anterior-posterior (θ_{Sag}) planes. Negative values represent right lateral or posterior direction, and positive values represent left lateral or anterior direction. Differences between the male and female vector directions are shown, which are the absolute difference in degrees. Significant differences between males and females are indicated when p≤0.05.

Right Psoas Major - Muscle Vector Directions (degrees) in the Anterior-Posterior and Lateral Planes

Level	Female θ_{Lat} mean[A] (s.d.)	Male θ_{Lat} mean[A] (s.d.)	Difference[B]	Female θ_{Sag} mean[A] (s.d.)	Male θ_{Sag} mean[A] (s.d.)	Difference[B]
T8						
T9						
T10						
T11						
T12						
L1	8.1 (3.2)	7.5 (-)	0.6	19.7 (17.3)	-2.8 (-)	22.5
L2	8.6 (2.0)	10.6 (3.6)	4.0	11.9 (6.8)	7.2 (3.7)	4.7
L3	12.1 (2.4)	11.3 (2.9)	0.8	2.1 (6.6)	4.5 (4.7)	2.4
L4	13.9 (3.4)	11.3 (4.0)	2.6	-20.4 (11.2)	-13.4 (7.5)	7.0
L5	13.0 (6.2)	9.8 (3.7)	3.2	-43.8 (11.6)	-39.1 (6.3)	4.7

A = Degrees
B = Shaded cells represent significant difference between females and males.

Table 1.57. Left Psoas Major mean (s.d.) muscle vector directions (degrees) in the lateral (θ_{Lat}) and anterior-posterior (θ_{Sag}) planes. Negative values represent right lateral or posterior direction, and positive values represent left lateral or anterior direction. Differences between the male and female vector directions are shown, which are the absolute difference in degrees. Significant differences between males and females are indicated when p≤0.05.

Left Psoas Major - Muscle Vector Directions (degrees) in the Anterior-Posterior and Lateral Planes

Level	Female θ_{Lat} mean[A] (s.d.)	Male θ_{Lat} mean[A] (s.d.)	Difference[B]	Female θ_{Sag} mean[A] (s.d.)	Male θ_{Sag} mean[A] (s.d.)	Difference[B]
T8						
T9						
T10						
T11						
T12						
L1	-10.5 (3.9)	-10.9 (3.6)	0.4	19.5 (17.7)	0.4 (10.3)	19.1
L2	-8.9 (2.5)	-8.0 (2.6)	1.0	15.0 (6.3)	6.5 (4.3)	8.5
L3	-9.0 (2.7)	-7.9 (2.5)	1.1	2.8 (4.9)	5.4 (3.9)	2.6
L4	-8.9 (3.0)	-7.5 (2.6)	1.4	-17.2 (11.9)	-11.5 (10.8)	5.7
L5	-9.1 (3.9)	-4.0 (3.2)	5.1	-46.4 (10.5)	-38.7 (7.4)	7.7

A = Degrees
B = Shaded cells represent significant difference between females and males.

Table 1.58. Right Quadratus Lumborum mean (s.d.) muscle vector directions (degrees) in the lateral (θ_{Lat}) and anterior-posterior (θ_{Sag}) planes. Negative values represent right lateral or posterior direction, and positive values represent left lateral or anterior direction. Differences between the male and female vector directions are shown, which are the absolute difference in degrees. Significant differences between males and females are indicated when $p \leq 0.05$.

Right Quadratus Lumborum - Muscle Vector Directions (degrees) in the Anterior-Posterior and Lateral Planes

Level	Female θ_{Lat} mean[A] (s.d.)	Male θ_{Lat} mean[A] (s.d.)	Difference[B]	Female θ_{Sag} mean[A] (s.d.)	Male θ_{Sag} mean[A] (s.d.)	Difference[B]
T8						
T9						
T10						
T11						
T12						
L1	3.3 (9.1)	12.2 (-)	8.9	13.0 (10.2)	4.5 (-)	8.5
L2	21.0 (7.2)	21.9 (4.4)	0.9	14.6 (9.5)	12.4 (4.0)	2.2
L3	23.4 (4.2)	16.8 (12.3)	6.6	2.6 (8.8)	7.0 (4.7)	4.4
L4	23.3 (-)			-15.0 (-)		
L5						

A = Degrees
B = Shaded cells represent significant difference between females and males.

Table 1.59. Left Quadratus Lumborum mean (s.d.) muscle vector directions (degrees) in the lateral (θ_{Lat}) and anterior-posterior (θ_{Sag}) planes. Negative values represent right lateral or posterior direction, and positive values represent left lateral or anterior direction. Differences between the male and female vector directions are shown, which are the absolute difference in degrees. Significant differences between males and females are indicated when $p \leq 0.05$.

Left Quadratus Lumborum - Muscle Vector Directions (degrees) in the Anterior-Posterior and Lateral Planes

Level	Female θ_{Lat} mean[A] (s.d.)	Male θ_{Lat} mean[A] (s.d.)	Difference[B]	Female θ_{Sag} mean[A] (s.d.)	Male θ_{Sag} mean[A] (s.d.)	Difference[B]
T8						
T9						
T10						
T11						
T12						
L1	-11.1 (3.9)	-17.1 (0.2)	6.0	18.6 (8.6)	8.5 (2.8)	10.1
L2	-23.8 (8.4)	-23.7 (11.3)	0.1	19.1 (8.8)	11.4 (3.1)	7.7
L3	-17.3 (7.7)	-12.4 (13.7)	4.9	2.7 (7.4)	9.7 (6.3)	7.0
L4	-20.6 (-)			-10.5 (-)		
L5						

A = Degrees
B = Shaded cells represent significant difference between females and males.

Table 1.60. Vertebral body mean (s.d.) muscle vector directions (degrees) in the lateral (θ_{Lat}) and anterior-posterior (θ_{Sag}) planes. Negative values represent right lateral or posterior direction, and positive values represent left lateral or anterior direction. Differences between the male and female vector directions are shown, which are the absolute difference in degrees. Significant differences between males and females are indicated when p≤0.05.

Vertebral Body - Muscle Vector Directions (degrees) in the Anterior-Posterior and Lateral Planes

Level	Female θ_{Lat} mean[A] (s.d.)	Male θ_{Lat} mean[A] (s.d.)	Difference[B]	Female θ_{Sag} mean[A] (s.d.)	Male θ_{Sag} mean[A] (s.d.)	Difference[B]
T8	-0.3 (2.5)	0.8 (2.0)	1.1	3.6 (3.0)	1.8 (3.3)	1.8
T9	1.5 (2.7)	1.2 (2.6)	0.3	6.5 (3.4)	4.3 (3.1)	2.2
T10	0.3 (2.4)	0.9 (2.8)	0.6	8.3 (5.0)	4.0 (3.8)	4.3 p=0.0210
T11	-0.2 (3.3)	0.2 (2.5)	0.4	9.8 (5.6)	6.6 (3.9)	3.2 p=0.0129
T12	-0.9 (3.4)	-0.2 (2.9)	0.7	12.7 (3.8)	11.2 (5.7)	1.5
L1	-1.3 (2.4)	-0.7 (2.3)	0.6	14.9 (3.8)	12.0 (5.0)	2.9
L2	-0.6 (2.9)	1.2 (2.9)	1.8	14.0 (3.9)	11.4 (2.5)	2.6
L3	0.6 (2.7)	0.1 (2.8)	0.5	8.6 (3.1)	9.1 (1.8)	0.5
L4	2.4 (3.8)	1.9 (2.5)	0.5	-3.7 (7.2)	0.4 (4.2)	4.1
L5	5.4 (5.1)	3.0 (3.3)	2.4	-22.0 (10.7)	-15.4 (5.7)	6.6 p=0.0565

A = Degrees
B = Shaded cells represent significant difference between females and males.

Table 1.61. Significant regression equations predicting the largest female cross-sectional muscle area based on external anthropometric measures. Significant equations are represented by shaded cells ($p \leq 0.05$). Each muscle is the average of the largest right and left side, irrespective of the levels.

Measure	Average of Right and Left Largest Muscle						
Location	Latissimus Dorsi	Erector Spinae	Rectus Abdominis	External Obliques	Internal Obliques	Psoas Major	Quad. Lumborum
IC	0.6184	0.5375	0.5480	0.1851	0.6290	0.7890	0.5983
XP	0.0054	0.0018	0.0057	0.0070	0.0002	0.2983	0.0139
BMI	0.1213	0.0006	0.0239	0.1032	0.0006	0.3578	0.0565

IC = Iliac Crest;
XP = Xyphoid Process;
BMI = Body Mass Index.

Table 1.62. Significant regression equations predicting the largest female cross-sectional muscle area based on external anthropometric measures. Significant equations are represented by shaded cells ($p \leq 0.05$).

Measure	Right or Left Muscle													
Location	RLAT	LLAT	RES	LES	RABD	LABD	REOB	LEOB	RIOB	LIOB	RPSS	LPSS	RQLM	LQLM
IC	0.7669	0.4853	0.5492	0.5283	0.5411	0.5572	0.4041	0.0768	0.5228	0.7981	0.4868	0.9031	0.8564	0.6167
XP	0.0044	0.0078	0.0020	0.0020	0.0040	0.0082	0.0255	0.0035	0.0003	0.0005	0.3121	0.3475	0.0133	0.0408
BMI	0.0795	0.1886	0.0005	0.0008	0.0172	0.0323	0.2479	0.0435	0.0004	0.0030	0.2544	0.5234	0.0534	0.4210

IC = Iliac Crest;
XP = Xyphoid Process;
BMI = Body Mass Index.

Table 1.63. Significant regression equations predicting the largest male cross-sectional muscle area based on external anthropometric measures. Significant equations are represented by shaded cells ($p \leq 0.05$). Each muscle is the average of the largest right and left side, irrespective of the levels.

Measure	Average of Right and Left Largest Muscle						
Location	Latissimus Dorsi	Erector Spinae	Rectus Abdominis	External Obliques	Internal Obliques	Psoas Major	Quad. Lumborum
IC	0.3516	0.2380	0.1755	0.2383	0.0584	0.5419	0.0755
XP	0.0553	0.0903	0.0567	0.0097	0.0369	0.1067	0.1240
BMI	0.1171	0.0271	0.0267	0.1243	0.0869	0.6131	0.5105

IC = Iliac Crest;
XP = Xyphoid Process;
BMI = Body Mass Index.

Table 1.64. Significant regression equations predicting the largest male cross-sectional muscle area based on external anthropometric measures. Significant equations are represented by shaded cells ($p \leq 0.05$).

Measure	Right or Left Muscle													
Location	RLAT	LLAT	RES	LES	RABD	LABD	REOB	LEOB	RIOB	LIOB	RPSS	LPSS	RQLM	LQLM
IC	0.4755	0.2951	0.2652	0.2213	0.1521	0.2090	0.3551	0.1870	0.1075	0.0589	0.4758	0.6440	0.1039	0.0686
XP	0.1516	0.0282	0.1064	0.0819	0.0274	0.1034	0.0175	0.0134	0.0862	0.0356	0.0908	0.1436	0.1610	0.1131
BMI	0.0986	0.1632	0.0248	0.0328	0.0215	0.0376	0.0820	0.2161	0.2110	0.0536	0.5990	0.6420	0.4123	0.6243

IC = Iliac Crest;
XP = Xyphoid Process;
BMI = Body Mass Index.

Table 1.65. Regression equations predicting the Cross-sectional area (cm^2) of the Latissimus Dorsi for Females and Males from various anthropometric measures. Equations were developed for the cross-sectional area of the latissimus dorsi (to represent both the right and left side) using the average of the largest left and right latissimus dorsi, for the right latissimus dorsi, and the left latissimus dorsi. Significant regression equations are indicated by shaded rows when $p \leq 0.05$.

Latissimus Dorsi - Regression Equations Predicting Cross-Sectional Muscle Areas for Females and Males.

Muscle	p-value male vs female regression equation	Females			Males		
		Regression Equation	R^2	p-value	Regression Equation	R^2	p-value
Average of Largest Right and Left Latissimus Dorsi	0.4833	**-7.96 + 0.041TDTWXP**	**0.374**	**0.0054**	**-0.406 + 0.029TDTWXP**	**0.386**	**0.0553**
	0.0007	15.8 - 0.006TDTWIC	0.014	0.6184	10.89 + 0.015TDTWIC	0.109	0.3516
	0.0012	10.55 + 0.003TDTWTR	0.003	0.8093	6.98 + 0.0164TDTWTR	0.147	0.2744
	0.0541	-2.25 + 0.7BMI	0.128	0.1213	-8.97 + 1.16BMI	0.278	0.1171
Right Latissimus Dorsi	0.2113	**-8.17 + 0.043TDTWXP**	**0.388**	**0.0044**	6.73 + 0.021TDTWXP	0.239	0.1516
	0.0006	15.3 - 0.004TDTWIC	0.005	0.7669	14.92 + 0.01TDTWIC	0.066	0.4755
	0.0008	9.78 + .005TDTWTR	0.010	0.6670	15.3 + 0.008TDTWTR	0.041	0.5753
	0.0504	-3.67 + 0.8BMI	0.161	0.0795	-6.4 + 1.11BMI	0.304	0.0986
Left Latissimus Dorsi	0.5959	**-7.75 + 0.04TDTWXP**	**0.349**	**0.0078**	**-7.54 + 0.037TDTWXP**	**0.472**	**0.0282**
	0.0012	16.31 - 0.008TDTWIC	0.027	0.4853	6.84 + 0.019TDTWIC	0.136	0.2951
	0.0017	11.32 + .001TDTWTR	0.000	0.9545	-1.35 + 0.024TDTWTR	0.252	0.1395
	0.0660	-0.829 + 0.596BMI	0.094	0.1886	-11.54 + 1.22BMI	0.228	0.1632

TDTWXP = Trunk Depth x Trunk Width (cm^2) measured at the Xyphoid Process;
TDTWTR = Trunk Depth x Trunk Width (cm^2) measured at the Iliac Crest;
TDTWIC = Trunk Depth x Trunk Width (cm^2) measured at the Trochanter;
BMI = Weight / Height^2 (kg/m^2).

Table 1.66. Regression equations predicting the Cross-sectional area (cm^2) of the Erector Spinae for Females and Males from various anthropometric measures. Equations were developed for the cross-sectional area of the erector spinae (to represent both the right and left side) using the average of the largest left and right erector spinae, for the right erector spinae, and the left erector spinae. Significant regression equations are indicated by shaded rows when $p \leq 0.05$.

Erector Spinae - Regression Equations Predicting Cross-Sectional Muscle Areas for Females and Males.

Muscle	p-value male vs female regression equation	Females			Males		
		Regression Equation	R^2	p-value	Regression Equation	R^2	p-value
Average of Largest Right and Left Erector Spinae	0.0226	**0.533 + 0.035TDTWXP**	**0.445**	**0.0018**	13.58 + 0.02TDTWXP	0.317	0.0903
	0.0000	14.81 + 0.006TDTWIC	0.022	0.5375	18.91 + 0.014TDTWIC	0.169	0.2380
	0.0000	8.39 + .012TDTWTR	0.128	0.1211	**10.34 + 0.021TDTWTR**	**0.417**	**0.0437**
	0.0004	**-4.25 + 1.045BMI**	**0.491**	**0.0006**	**-1.85 + 1.19BMI**	**0.477**	**0.0271**
Right Erector Spinae	0.0196	**-0.302 + 0.036TDTWXP**	**0.440**	**0.0020**	14.74 + 0.019TDTWXP	0.293	0.1064
	0.0000	14.5 + 0.006TDTWIC	0.020	0.5492	19.82 + 0.013TDTWIC	0.152	0.2652
	0.0000	8.65 + .012TDTWTR	0.099	0.1762	**11.06 + 0.02TDTWTR**	**0.415**	**0.0443**
	0.0007	**-6.47 + 1.14BMI**	**0.496**	**0.0005**	**-1.1 + 1.16BMI**	**0.487**	**0.0248**
Left Erector Spinae	0.0280	**2.79 + 0.03TDTWXP**	**0.440**	**0.0020**	12.42 + 0.022TDTWXP	0.331	0.0819
	0.0000	15.13 + 0.005TDTWIC	0.023	0.5283	18.01 + 0.016TDTWIC	0.180	0.2213
	0.0000	8.12 + .013TDTWTR	0.164	0.0766	**9.61 + 0.021TDTWTR**	**0.407**	**0.0473**
	0.0003	**-2.04 + 0.947BMI**	**0.474**	**0.0008**	**-2.6 + 1.21BMI**	**0.454**	**0.0328**

TDTWXP = Trunk Depth x Trunk Width (cm^2) measured at the Xyphoid Process;
TDTWTR = Trunk Depth x Trunk Width (cm^2) measured at the Iliac Crest;
TDTWIC = Trunk Depth x Trunk Width (cm^2) measured at the Trochanter;
BMI = Weight / Height^2 (kg/m^2).

Table 1.67. Regression equations predicting the Cross-sectional area (cm^2) of the Rectus Abdominis for Females and Males from various anthropometric measures. Equations were developed for the cross-sectional area of the rectus abdominis (to represent both the right and left side) using the average of the largest left and right rectus abdominis, for the right rectus abdominis, and the left rectus abdominis. Significant regression equations are indicated by shaded rows when $p \leq 0.05$.

Rectus Abdominis - Regression Equations Predicting Cross-Sectional Muscle Areas for Females and Males.

Muscle	p-value male vs female regression equation	Females			Males		
		Regression Equation	R^2	p-value	Regression Equation	R^2	p-value
Average of Largest Right and Left Rectus Abdominis	0.4751	**-2.0 + 0.015TDTWXP**	**0.370**	**0.0057**	**-0.386 + 0.012TDTWXP**	**0.383**	**0.0567**
	0.0018	7.07 - 0.003TDTWIC	0.020	0.5480	2.55 + 0.009TDTWIC	0.216	0.1755
	0.0025	5.29 + 0.0004TDTWTR	0.001	0.9199	-0.139 + 0.01TDTWTR	0.322	0.0871
	0.1833	**-2.16 + 0.366BMI**	**0.253**	**0.0239**	**-7.81 + 0.632BMI**	**0.479**	**0.0267**
Right Rectus Abdominis	0.5628	**-1.39 + 0.014TDTWXP**	**0.394**	**0.0040**	**-0.72 + 0.012TDTWXP**	**0.475**	**0.0274**
	0.0007	6.84 - 0.002TDTWIC	0.021	0.5411	2.64 - 0.008TDTWIC	0.239	0.1521
	0.0010	5.11 + 0.001TDTWTR	0.001	0.0766	0.03 + 0.009TDTWTR	0.356	0.0686
	0.1112	**-1.63 + 0.338BMI**	**0.277**	**0.0172**	**-7.01 + 0.596BMI**	**0.504**	**0.0215**
Left Rectus Abdominis	0.4142	**-2.62 + 0.017TDTWXP**	**0.345**	**0.0082**	-0.054 + 0.012TDTWXP	0.297	0.1034
	0.0041	7.3 - 0.003TDTWIC	0.020	0.5572	2.46 + 0.009TDTWIC	0.189	0.2090
	0.0058	5.48 + 0.0002TDTWTR	0.000	0.9542	-0.309 + 0.01TDTWTR	0.281	0.1153
	0.2685	**-2.69 + 0.395BMI**	**0.230**	**0.0323**	**-8.61 + 0.667BMI**	**0.436**	**0.0376**

TDTWXP = Trunk Depth x Trunk Width (cm^2) measured at the Xyphoid Process;
TDTWTR = Trunk Depth x Trunk Width (cm^2) measured at the Iliac Crest;
TDTWIC = Trunk Depth x Trunk Width (cm^2) measured at the Trochanter;
BMI = Weight / $Height^2$ (kg/m^2).

Table 1.68. Regression equations predicting the Cross-sectional area (cm^2) of the External Obliques for Females and Males from various anthropometric measures. Equations were developed for the cross-sectional area of the external obliques (to represent both the right and left side) using the average of the largest left and right external obliques, for the right external obliques, and the left external obliques. Significant regression equations are indicated by shaded rows when $p \leq 0.05$.

External Obliques - Regression Equations Predicting Cross-Sectional Muscle Areas for Females and Males.

Muscle	p-value male vs female regression equation	Females			Males		
		Regression Equation	R^2	p-value	Regression Equation	R^2	p-value
Average of Largest Right and Left External Obliques	0.0208	**2.92 + 0.008TDTWXP**	**0.356**	**0.0070**	**0.642 + 0.014TDTWXP**	**0.588**	**0.0097**
	0.0000	5.31 + 0.003TDTWIC	0.095	0.1851	6.29 + 0.008TDTWIC	0.169	0.2383
	0.0000	4.9 + 0.003TDTWTR	0.091	0.1969	2.85 + 0.01TDTWTR	0.330	0.0823
	0.0000	3.86 + 0.151BMI	0.141	0.1032	-0.615 + 0.468BMI	0.269	0.1243
Right External Obliques	0.0579	**3.34 + 0.008TDTWXP**	**0.261**	**0.0255**	**1.27 + 0.013TDTWXP**	**0.527**	**0.0175**
	0.0000	6.04 + 0.002TDTWIC	0.039	0.4041	7.3 + 0.006TDTWIC	0.108	0.3551
	0.0000	5.14 + 0.003TDTWTR	0.072	0.2512	4.28 + 0.008TDTWTR	0.230	0.1606
	0.0001	4.71 + 0.1225BMI	0.073	0.2479	-1.82 + 0.512BMI	0.331	0.0820
Left External Obliques	0.0169	**2.495 + 0.009TDTWXP**	**0.403**	**0.0035**	**0.014 + 0.015TDTWXP**	**0.555**	**0.0134**
	0.0000	4.57 + 0.004TDTWIC	0.164	0.0768	5.28 + 0.009TDTWIC	0.207	0.1870
	0.0000	4.66 + 0.003TDTWTR	0.094	0.1875	1.43 + 0.011TDTWTR	0.380	0.0577
	0.0000	**3.0 + 0.18BMI**	**0.208**	**0.0435**	0.588 + 0.424BMI	0.184	0.2161

TDTWXP = Trunk Depth x Trunk Width (cm^2) measured at the Xyphoid Process;
TDTWTR = Trunk Depth x Trunk Width (cm^2) measured at the Iliac Crest;
TDTWIC = Trunk Depth x Trunk Width (cm^2) measured at the Trochanter;
BMI = Weight / Height^2 (kg/m^2).

Table 1.69. Regression equations predicting the Cross-sectional area (cm^2) of the Internal Obliques for Females and Males from various anthropometric measures. Equations were developed for the cross-sectional area of the internal obliques (to represent both the right and left side) using the average of the largest left and right internal obliques, for the right internal obliques, and the left internal obliques. Significant regression equations are indicated by shaded rows when $p \leq 0.05$.

Internal Obliques - Regression Equations Predicting Cross-Sectional Muscle Areas for Females and Males.

Muscle	p-value male vs female regression equation	Females			Males		
		Regression Equation	R^2	p-value	Regression Equation	R^2	p-value
Average of Largest Right and Left Internal Obliques	0.6260	**-2.37 + 0.017TDTWXP**	**0.613**	**0.0002**	**-1.47 + 0.016TDTWXP**	**0.439**	**0.0369**
	0.0000	4.83+ 0.002TDTWIC	0.015	0.6290	**0.677 + 0.015TDTWIC**	**0.378**	**0.0584**
	0.0000	3.74 + 0.003TDTWTR	0.040	0.4290	1.16 + 0.011TDTWTR	0.239	0.1516
	0.0000	**-4.25 + 0.48BMI**	**0.530**	**0.0006**	-6.45 + 0.663BMI	0.322	0.0869
Right Internal Obliques	0.6843	**-3.457 + 0.019TDTWXP**	**0.591**	**0.0003**	-0.731 + 0.015TDTWXP	0.324	0.0862
	0.0009	4.31 + 0.003TDTWIC	0.026	0.5228	1.05 + 0.014TDTWIC	0.291	0.1075
	0.0005	3.5 + 0.003TDTWTR	0.037	0.4449	3.38 + 0.008TDTWTR	0.114	0.3402
	0.0798	**-6.08 + 0.568BMI**	**0.557**	**0.0004**	-3.58 + 0.543BMI	0.188	0.2110
Left Internal Obliques	0.3244	**-1.28 + 0.014TDTWXP**	**0.565**	**0.0005**	**-2.59 + 0.018TDTWXP**	**0.491**	**0.0356**
	0.0000	5.35 + 0.001TDTWIC	0.004	0.7981	**-1.35 + 0.018TDTWIC**	**0.421**	**0.0589**
	0.0000	3.97 + 0.002TDTWTR	0.038	0.4389	-2.39 + 0.015TDTWTR	0.362	0.0866
	0.0033	**-2.424 + 0.393BMI**	**0.433**	**0.0030**	**-8.7 + 0.762BMI**	**0.434**	**0.0536**

TDTWXP = Trunk Depth x Trunk Width (cm^2) measured at the Xyphoid Process;
TDTWTR = Trunk Depth x Trunk Width (cm^2) measured at the Iliac Crest;
TDTWIC = Trunk Depth x Trunk Width (cm^2) measured at the Trochanter;
BMI = Weight / Height^2 (kg/m^2).

Table 1.70. Regression equations predicting the Cross-sectional area (cm^2) of the Psoas Major for Females and Males from various anthropometric measures. Equations were developed for the cross-sectional area of the psoas major (to represent both the right and left side) using the average of the largest left and right psoas major, for the right psoas major, and the left psoas major. Significant regression equations are indicated by shaded rows when $p \leq 0.05$.

Psoas Major - Regression Equations Predicting Cross-Sectional Muscle Areas for Females and Males.

Muscle	p-value male vs female regression equation	Females			Males		
		Regression Equation	R^2	p-value	Regression Equation	R^2	p-value
Average of Largest Right and Left Psoas Major	0.0000	7.63 + 0.004TDTWXP	0.063	0.2983	7.18 + 0.015TDTWXP	0.292	0.1067
	0.0000	9.26 + 0.001TDTWIC	0.004	0.7890	14.41 + 0.006TDTWIC	0.048	0.5419
	0.0000	9.06 + 0.001TDTWTR	0.005	0.7681	11.39 + 0.008TDTWTR	0.103	0.3670
	0.0000	7.22 + 0.120BMI	0.047	0.3578	12.17 + 0.246BMI	0.033	0.6131
Right Psoas Major	0.0001	7.35 + 0.004TDTWXP	0.060	0.3121	4.8 + 0.018TDTWXP	0.316	0.0908
	0.0000	8.19 + 0.002TDTWIC	0.027	0.4868	12.77 + 0.008TDTWIC	0.065	0.4758
	0.0000	7.59 + 0.002TDTWTR	0.037	0.4146	9.78 + 0.009TDTWTR	0.111	0.3479
	0.0000	6.39 + 0.144BMI	0.072	0.2544	10.7 + 0.29BMI	0.036	0.5990
Left Psoas Major	0.0000	7.91 + 0.005TDTWXP	0.052	0.3475	9.57 + 0.012TDTWXP	0.247	0.1436
	0.0000	10.33 - 0.0004TDTWIC	0.001	0.9031	16.06 + 0.004TDTWIC	0.028	0.6440
	0.0000	10.54 - 0.0006TDTWTR	0.002	0.8616	13.0 + 0.007TDTWTR	0.087	0.4076
	0.0000	8.05 + 0.096BMI	0.023	0.5234	13.65 + 0.201BMI	0.028	0.6420

TDTWXP = Trunk Depth x Trunk Width (cm^2) measured at the Xyphoid Process;
TDTWTR = Trunk Depth x Trunk Width (cm^2) measured at the Iliac Crest;
TDTWIC = Trunk Depth x Trunk Width (cm^2) measured at the Trochanter;
BMI = Weight / Height^2 (kg/m^2).

Table 1.71. Regression equations predicting the Cross-sectional area (cm^2) of the Quadratus Lumborum for Females and Males from various anthropometric measures. Equations were developed for the cross-sectional area of the quadratus lumborum (to represent both the right and left side) using the average of the largest left and right quadratus lumborum, for the right quadratus lumborum, and the left quadratus lumborum. Significant regression equations are indicated by shaded rows when $p \leq 0.05$.

Quadratus Lumborum - Regression Equations Predicting Cross-Sectional Muscle Areas for Females and Males.

Muscle	p-value male vs female regression equation	Females			Males		
		Regression Equation	R^2	p-value	Regression Equation	R^2	p-value
Average of Largest Right and Left Quadratus Lumborum	0.0026	**1.52 + 0.005TDTWXP**	**0.323**	**0.0139**	1.66 + 0.008TDTWXP	0.270	0.1240
	0.0000	3.43 + 0.001TDTWIC	0.017	0.5983	1.68 + 0.009TDTWIC	0.343	0.0755
	0.0000	3.23 + 0.0TDTWTR	0.022	0.5457	**-1.15 + 0.01TDTWTR**	**0.515**	**0.0194**
	0.0000	**1.56 + 0.108BMI**	**0.198**	**0.0565**	3.17 + 0.178BMI	0.056	0.5105
Right Quadratus Lumborum	0.0008	**1.05 + 0.005TDTWXP**	**0.326**	**0.0133**	2.26 + 0.007TDTWXP	0.230	0.1610
	0.0000	3.35 + 0.0003TDTWIC	0.002	0.8564	2.23 + 0.008TDTWIC	0.296	0.1039
	0.0000	2.86 + 0.001TDTWTR	0.021	0.5542	**-0.333 + 0.009TDTWTR**	**0.450**	**0.0337**
	0.0000	**1.08 + 0.114BMI**	**0.202**	**0.0534**	2.22 + 0.211BMI	0.086	0.4123
Left Quadratus Lumborum	0.0327	**1.6 + 0.006TDTWXP**	**0.224**	**0.0408**	1.06 + 0.009TDTWXP	0.284	0.1131
	0.0000	3.76 + 0.001TDTWIC	0.014	0.6167	1.12 + 0.01TDTWIC	0.356	0.0686
	0.0000	3.93 + 0.0005TDTWTR	0.004	0.7830	**-1.98 + 0.011TDTWTR**	**0.531**	**0.0168**
	0.0000	2.96 + 0.065BMI	0.036	0.4210	4.11 + 0.145BMI	0.031	0.6243

TDTWXP = Trunk Depth x Trunk Width (cm^2) measured at the Xyphoid Process;
TDTWTR = Trunk Depth x Trunk Width (cm^2) measured at the Iliac Crest;
TDTWIC = Trunk Depth x Trunk Width (cm^2) measured at the Trochanter;
BMI = Weight / Height^2 (kg/m^2).

Table 1.72. Regression equations predicting the lateral and sagittal moment arm (cm) of the muscle centroid of the right Latissimus Dorsi to the centroid of the vertebral body for Females and Males from various anthropometric measures. Equations were developed for insertions of the right latissimus dorsi at T_8 and the origin at L_2. Significant regression equations are indicated by shaded rows when $p \leq 0.05$.

Right Latissimus Dorsi - Regression Equations Predicting Muscle Moment Arms for Females and Males.

Plane/Location	Females			Males *		
	Regression Equation	R^2	p-value	Regression Equation	R^2	p-value
Lateral/Origin (L_2)	**-2.75 - 0.244TWXP**	**0.195**	**0.0514**	**2.30 + 0.254TWXP**	**0.425**	**0.0410**
	-9.75 + 0.015TWIC	0.001	0.8853	**3.54 + 0.231TWIC**	**0.424**	**0.0412**
	-5.49 - 0.181BMI	**0.191**	**0.0538**	**3.66 + 0.268BMI**	**0.601**	**0.0085**
Sagittal Origin (L_2)	-1.0 - 0.133TDXP	0.043	0.3782	-7.28 + 0.147TDXP	0.093	0.3926
	0.454 - 0.197TDIC	0.142	0.1014	-2.15 - 0.08TDIC	0.029	0.6409
	-2.09 - 0.064BMI	0.021	0.5461	-6.21 + 0.089BMI	0.038	0.5922
Lateral/Insertion (T_8)	**-6.81 - 0.236TWXP**	**0.203**	**0.0458**	**-5.08 - 0.316TWXP**	**0.440**	**0.0367**
	-12.35 - 0.03TWIC	0.005	0.7645	-12.89 - 0.08TWIC	0.034	0.6112
	-9.46 - 0.175BMI	**0.200**	**0.0483**	-14.64 - 0.026BMI	0.004	0.8665
Sagittal Insertion (T_8)	-2.81 + 0.066TDXP	0.009	0.6883	-0.029 - 0.08TDXP	0.038	0.5909
	-0.429 - 0.059TDIC	0.011	0.6646	-1.0 - 0.038TDIC	0.009	0.7949
	-0.384 - 0.057BMI	0.014	0.6216	0.85 - 0.105BMI	0.072	0.4522

TDXP = Trunk Depth measured at the Xyphoid Process (cm);
TDIC = Trunk Depth measured at the Iliac Crest (cm);
TWXP = Trunk Depth measured at the Xyphoid Process (cm);
TWIC = Trunk Width measured at the Iliac Crest (cm);
BMI = Body Mass Index (kg/m^2).
* The Insertion Level for the Males was at L_3, not L_2.

Table 1.73. Regression equations predicting the lateral and sagittal moment arm (cm) of the muscle centroid of the left Latissimus Dorsi to the centroid of the vertebral body for Females and Males from various anthropometric measures. Equations were developed for insertions of the left latissimus dorsi at T_8 and the origin at L_2. Significant regression equations are indicated by shaded rows when $p \leq 0.05$.

Left Latissimus Dorsi - Regression Equations Predicting Muscle Moment Arms for Females and Males.

Plane/Location	Females			Males*		
	Regression Equation	R^2	p-value	Regression Equation	R^2	p-value
Lateral/Origin (L_2)	**1.67 + 0.287TWXP**	**0.222**	**0.0360**	**2.30 + 0.254TWXP**	**0.425**	**0.0410**
	10.39 - 0.035TWIC	0.005	0.7619	**3.54 + 0.231TWIC**	**0.424**	**0.0412**
	6.03 + 0.16BMI	0.122	0.1312	**3.66 + 0.268BMI**	**0.601**	**0.0085**
Sagittal Origin (L_2)	-3.75 - 0.007TDXP	0.000	0.9639	-7.28 + 0.147TDXP	0.093	0.3926
	-4.85 + 0.049TDIC	0.009	0.6863	-2.15 - 0.08TDIC	0.029	0.6409
	-3.63 - 0.011BMI	0.001	0.9124	-6.21 + 0.089BMI	0.038	0.5922
Lateral/Insertion (T_8)	8.4 + 0.173TWXP	0.134	0.1125	9.15 + 0.181TWXP	0.263	0.1297
	14.14 - 0.038TWIC	0.010	0.6723	11.78 + 0.107TWIC	0.110	0.3490
	10.77 + 0.109BMI	0.094	0.1880	13.22 + 0.07BMI	0.049	0.5372
Sagittal Insertion (T_8)	-5.1 + 0.24TDXP	0.169	0.0719	-2.19 + 0.065TDXP	0.016	0.7306
	-1.61 + 0.047TDIC	0.010	0.6788	-0.62 - 0.004TDIC	0.000	0.9830
	-1.48 + 0.038BMI	0.009	0.6984	-4.06 + 0.131BMI	0.070	0.4600

TDXP = Trunk Depth measured at the Xyphoid Process (cm);
TDIC = Trunk Depth measured at the Iliac Crest (cm);
TWXP = Trunk Depth measured at the Xyphoid Process (cm);
TWIC = Trunk Width measured at the Iliac Crest (cm);
BMI = Body Mass Index (kg/m^2).
* The Insertion Level for the Males was at L_3, not L_2.

Table 1.74. Regression equations predicting the lateral and sagittal moment arm (cm) of the muscle centroid of the right Erector Spinae to the centroid of the vertebral body for Females and Males from various anthropometric measures. Equations were developed for insertions of the right erector spinae at T_8 and the origin at L_5. Significant regression equations are indicated by shaded rows when $p \leq 0.05$.

Right Erector Spinae - Regression Equations Predicting Muscle Moment Arms for Females and Males.

Plane/Location	Females			Males		
	Regression Equation	R^2	p-value	Regression Equation	R^2	p-value
Lateral/Origin (L_5)	-2.69 - 0.003TWXP	0.000	0.9639	-6.58 + 0.112TWXP	0.119	0.3283
	-2.14 - 0.016TWIC	0.005	0.7683	-4.6 + 0.054TWIC	0.034	0.6098
	-2.65 + 0.002BMI	0.000	0.9681	-2.74 - 0.008BMI	0.001	0.9363
Sagittal Origin (L_5)	-5.11 - 0.017TDXP	0.004	0.7970	-3.43 - 0.116TDXP	0.140	0.2861
	-5.28 - 0.007TDIC	0.001	0.8998	-4.23 - 0.083TDIC	0.076	0.4416
	-6.29 + 0.041BMI	0.046	0.3636	-3.80 - 0.089BMI	0.091	0.3977
Lateral/Insertion (T_8)	-2.12 - 0.019TWXP	0.014	0.6240	-1.72 - 0.043TWXP	0.140	0.2860
	-2.05 - 0.021TWIC	0.026	0.4994	-2.21 - 0.029TWIC	0.081	0.4254
	-2.59 - 0.002BMI	0.000	0.9419	-2.38 - 0.028BMI	0.077	0.4385
Sagittal Insertion (T_8)	**-2.76 - 0.089TDXP**	**0.231**	**0.0320**	-3.63 - 0.069TDXP	0.157	0.2574
	-3.66 - 0.037TDIC	0.060	0.2989	-5.01 - 0.009TDIC	0.003	0.8812
	-3.63 - 0.036BMI	0.078	0.2326	-4.33 - 0.035BMI	0.043	0.5671

TDXP = Trunk Depth measured at the Xyphoid Process (cm);
TDIC = Trunk Depth measured at the Iliac Crest (cm);
TWXP = Trunk Depth measured at the Xyphoid Process (cm);
TWIC = Trunk Width measured at the Iliac Crest (cm);
BMI = Body Mass Index (kg/m^2).

Table 1.75. Regression equations predicting the lateral and sagittal moment arm (cm) of the muscle centroid of the left Erector Spinae to the centroid of the vertebral body for Females and Males from various anthropometric measures. Equations were developed for insertions of the left erector spinae at T_8 and the origin at L_5. Significant regression equations are indicated by shaded rows when $p \leq 0.05$.

Left Erector Spinae - Regression Equations Predicting Muscle Moment Arms for Females and Males.

Plane/Location	Females			Males		
	Regression Equation	R^2	p-value	Regression Equation	R^2	p-value
Lateral/Origin (L_5)	1.91 + 0.031TWXP	0.012	0.6501	6.85 - 0.114TWXP	0.229	0.1623
	1.89 + 0.03TWIC	0.018	0.5711	4.87 - 0.057TWIC	0.068	0.4655
	2.08 + 0.031BMI	0.021	0.5396	3.75 - 0.023BMI	0.012	0.7607
Sagittal Origin (L_5)	-5.34 - 0.02TDXP	0.004	0.8053	-5.29 - 0.035TDXP	0.011	0.7691
	-6.36 + 0.033TDIC	0.015	0.6109	-3.21 - 0.129TDIC	0.161	0.2508
	-6.9 + 0.057BMI	0.058	0.3047	-5.87 - 0.009BMI	0.001	0.9381
Lateral/Insertion (T_8)	0.798 + 0.068TWXP	0.109	0.1555	1.32 + 0.06TWXP	0.091	0.3961
	3.08 - 0.015TWIC	0.009	0.6983	1.12 + 0.071TWIC	0.154	0.2629
	1.86 + 0.038BMI	0.058	0.3072	1.08 + 0.086BMI	0.233	0.1581
Sagittal Insertion (T_8)	-3.75 - 0.023TDXP	0.023	0.5249	-4.32 - 0.023TDXP	0.010	0.7866
	-4.46 + 0.015TDIC	0.015	0.6104	-4.68 - 0.008TDIC	0.001	0.9249
	-4.27 + 0.005BMI	0.002	0.8454	-5.27 + 0.016BMI	0.005	0.8431

TDXP = Trunk Depth measured at the Xyphoid Process (cm);
TDIC = Trunk Depth measured at the Iliac Crest (cm);
TWXP = Trunk Depth measured at the Xyphoid Process (cm);
TWIC = Trunk Width measured at the Iliac Crest (cm);
BMI = Body Mass Index (kg/m^2).

Proprietary data of The Biodynamics Laboratory at The Ohio State University

Table 1.76. Regression equations predicting the lateral and sagittal moment arm (cm) of the muscle centroid of the right Rectus Abdominis to the centroid of the vertebral body for Females and Males from various anthropometric measures. Equations were developed for insertions of the right rectus abdominis at L_1 and the origin at L_5. Significant regression equations are indicated by shaded rows when $p \leq 0.05$.

Right Rectus Abdominis - Regression Equations Predicting Muscle Moment Arms for Females and Males.

Plane/Location	Females			Males		
	Regression Equation	R^2	p-value	Regression Equation	R^2	p-value
Lateral/Origin (L_5)	-3.86 + 0.001TWXP	0.000	0.9948	-4.34 + 0.007TWXP	0.001	0.9432
	-4.33 + 0.018TWIC	0.002	0.8456	-6.72 + 0.086TWIC	0.139	0.2891
	-4.97 + 0.053BMI	0.022	0.5339	-6.18 + 0.08BMI	0.128	0.3099
Sagittal Origin (L_5)	3.36 + 0.17TDXP	0.083	0.2195	**-1.53 + 0.398TDXP**	**0.380**	**0.0578**
	4.47 + 0.102TDIC	0.044	0.3749	**-0.959 + 0.383TDIC**	**0.368**	**0.0628**
	5.1 + 0.066BMI	0.025	0.5038	-0.871 + 0.329BMI	0.285	0.1118
Lateral/Insertion (L_1)	-1.52 - 0.07TWXP	0.022	0.5470	1.70 - 0.194TWXP	0.140	0.2877
	-2.41 - 0.035TWIC	0.009	0.6948	**5.35 - 0.329TWIC**	**0.482**	**0.0258**
	-1.33 - 0.0961BMI	0.060	0.3103	-0.729 - 0.151BMI	0.107	0.3570
Sagittal Insertion (L_1)	**3.28 + 0.342TDXP**	**0.381**	**0.0049**	**2.39 + 0.436TDXP**	**0.672**	**0.0037**
	5.57 + 0.201TDIC	0.184	0.0669	**3.89 + 0.38TDIC**	**0.536**	**0.0160**
	5.56 + 0.188BMI	0.176	0.0737	**1.98 + 0.405BMI**	**0.636**	**0.0057**

TDXP = Trunk Depth measured at the Xyphoid Process (cm);
TDIC = Trunk Depth measured at the Iliac Crest (cm);
TWXP = Trunk Depth measured at the Xyphoid Process (cm);
TWIC = Trunk Width measured at the Iliac Crest (cm);
BMI = Body Mass Index (kg/m^2).

Table 1.77. Regression equations predicting the lateral and sagittal moment arm (cm) of the muscle centroid of the left Rectus Abdominis to the centroid of the vertebral body for Females and Males from various anthropometric measures. Equations were developed for insertions of the left rectus abdominis at L_1 and the origin at L_5. Significant regression equations are indicated by shaded rows when $p \leq 0.05$.

Left Rectus Abdominis - Regression Equations Predicting Muscle Moment Arms for Females and Males.

Plane/Location	Females			Males		
	Regression Equation	R^2	p-value	Regression Equation	R^2	p-value
Lateral/Origin (L_5)	2.076 + 0.043TWXP	0.011	0.6575	**-4.16 + 0.229TWXP**	**0.339**	**0.0772**
	5.85 - 0.093TWIC	0.081	0.2227	-1.01 + 0.141TWIC	0.155	0.2600
	2.5 + 0.036BMI	0.013	0.6294	**-3.08 + 0.247BMI**	**0.502**	**0.0218**
Sagittal Origin (L_5)	2.35 + 0.205TDXP	0.122	0.1314	**-3.03 + 0.464TDXP**	**0.472**	**0.0283**
	3.12 + 0.151TDIC	0.099	0.1767	-0.359 + 0.356TDIC	0.292	0.1068
	4.3 + 0.086BMI	0.044	0.3767	**-1.99 + 0.373BMI**	**0.335**	**0.0794**
Lateral/Insertion (L_1)	**-1.29 + 0.184TWXP**	**0.225**	**0.0401**	-0.114 + 0.129TWXP	0.098	0.3774
	6.03 - 0.0837TWIC	0.077	0.2513	2.65 + 0.047TWIC	0.016	0.7313
	0.97 + 0.127BMI	0.155	0.0949	**-2.97 + 0.274BMI**	**0.566**	**0.0120**
Sagittal Insertion (L_1)	**1.86 + 0.426TDXP**	**0.452**	**0.0016**	**2.45 + 0.446TDXP**	**0.749**	**0.0012**
	4.42 + 0.266TDIC	**0.245**	**0.0312**	6.17 + 0.291TDIC	0.333	0.0805
	5.07 + 0.217BMI	0.179	0.0708	**1.05 + 0.452BMI**	**0.845**	**0.0002**

TDXP = Trunk Depth measured at the Xyphoid Process (cm);
TDIC = Trunk Depth measured at the Iliac Crest (cm);
TWXP = Trunk Depth measured at the Xyphoid Process (cm);
TWIC = Trunk Width measured at the Iliac Crest (cm);
BMI = Body Mass Index (kg/m^2).

Table 1.78. Regression equations predicting the lateral and sagittal moment arm (cm) of the muscle centroid of the right External Obliques to the centroid of the vertebral body for Females and Males from various anthropometric measures. Equations were developed for insertions of the right external oblique at L_1 and the origin at L_5. Significant regression equations are indicated by shaded rows when $p \leq 0.05$.

Right External Obliques - Regression Equations Predicting Muscle Moment Arms for Females and Males.

Plane/Location	Females			Males		
	Regression Equation	R^2	p-value	Regression Equation	R^2	p-value
Lateral/Origin (L_5)						
Sagittal Origin (L_5)						
Lateral/Insertion (L_1)	**-3.38 - 0.278TWXP**	**0.292**	**0.0140**	-4.06 - 0.275TWXP	0.231	0.1594
	-10.53 - 0.013TWIC	0.001	0.8962	**-1.18 - 0.39TWIC**	**0.560**	**0.0128**
	-5.67 - 0.246BMI	**0.405**	**0.0026**	-8.06 - 0.192BMI	0.142	0.2824
Sagittal Insertion (L_1)	4.88 + 0.038TDXP	0.003	0.8218	3.49 + 0.139TDXP	0.090	0.3995
	6.44 - 0.044TDIC	0.006	0.7540	2.5 + 0.187TDIC	0.171	0.2347
	5.76 - 0.009BMI	0.000	0.9429	3.7 + 0.116BMI	0.069	0.4642

TDXP = Trunk Depth measured at the Xyphoid Process (cm);
TDIC = Trunk Depth measured at the Iliac Crest (cm);
TWXP = Trunk Depth measured at the Xyphoid Process (cm);
TWIC = Trunk Width measured at the Iliac Crest (cm);
BMI = Body Mass Index (kg/m^2).

Table 1.79. Regression equations predicting the lateral and sagittal moment arm (cm) of the muscle centroid of the left External Oblique to the centroid of the vertebral body for Females and Males from various anthropometric measures. Equations were developed for insertions of the left external oblique at L_1 and the origin at L_5. Significant regression equations are indicated by shaded rows when $p \leq 0.05$.

Left External Obliques - Regression Equations Predicting Muscle Moment Arms for Females and Males.

Plane/Location	Females			Males		
	Regression Equation	R^2	p-value	Regression Equation	R^2	p-value
Lateral/Origin (L_5)						
Sagittal Origin (L_5)						
Lateral/Insertion (L_1)	**2.29 + 0.321TWXP**	**0.433**	**0.0016**	**1.76 + 0.334TWXP**	**0.522**	**0.0183**
	12.0 - 0.037TWIC	0.009	0.6898	5.99 + 0.218TWIC	0.268	0.1256
	6.16 + 0.227BMI	**0.383**	**0.0036**	**3.61 + 0.35BMI**	**0.728**	**0.0017**
Sagittal Insertion (L_1)	**-0.115 + 0.315TDXP**	**0.179**	**0.0628**	2.87 + 0.197TDXP	0.106	0.3585
	1.36 + 0.218TDIC	0.128	0.1213	8.4 - 0.046TDIC	0.006	0.8313
	3.86 + 0.086BMI	0.028	0.4846	-1.07 + 0.329BMI	0.324	0.0857

TDXP = Trunk Depth measured at the Xyphoid Process (cm);
TDIC = Trunk Depth measured at the Iliac Crest (cm);
TWXP = Trunk Depth measured at the Xyphoid Process (cm);
TWIC = Trunk Width measured at the Iliac Crest (cm);
BMI = Body Mass Index (kg/m^2).

Table 1.80. Regression equations predicting the lateral and sagittal moment arm (cm) of the muscle centroid of the right internal oblique to the centroid of the vertebral body for Females and Males from various anthropometric measures. Equations were developed for insertions of the right internal oblique at L_3 and the origin at L_5. Significant regression equations are indicated by shaded rows when $p \leq 0.05$.

Right Internal Obliques - Regression Equations Predicting Muscle Moment Arms for Females and Males.

Plane/Location	Females			Males		
	Regression Equation	R^2	p-value	Regression Equation	R^2	p-value
Lateral/Origin (L_5)						
A/P Origin (L_5)						
Lateral/Insertion (L_3)	**1.7 - 0.424TWXP**	**0.477**	**0.0015**	-6.94 - 0.142TWXP	0.126	0.3152
	-7.92 - 0.064TWIC	0.018	0.5927	**-4.65 - 0.228TWIC**	**0.390**	**0.0537**
	-0.967 - 0.416BMI	**0.677**	**0.0001**	-8.41 - 0.122BMI	0.118	0.3321
A/P Insertion (L_3)	**11.09 - 0.421TDXP**	**0.374**	**0.0069**	-0.51 + 0.17TDXP	0.077	0.4376
	5.75 - 0.121TDIC	0.045	0.3966	2.68 + 0.031TDIC	0.003	0.8861
	9.16 - 0.276BMI	**0.268**	**0.0277**	2.28 + 0.043BMI	0.005	0.8399

TDXP = Trunk Depth measured at the Xyphoid Process (cm);
TDIC = Trunk Depth measured at the Iliac Crest (cm);
TWXP = Trunk Depth measured at the Xyphoid Process (cm);
TWIC = Trunk Width measured at the Iliac Crest (cm);
BMI = Body Mass Index (kg/m^2).

Table 1.81. Regression equations predicting the lateral and sagittal moment arm (cm) of the muscle centroid of the left Internal Oblique to the centroid of the vertebral body for Females and Males from various anthropometric measures. Equations were developed for insertions of the left internal oblique at L_3 and the origin at L_5. Significant regression equations are indicated by shaded rows when $p \leq 0.05$.

Left Internal Obliques - Regression Equations Predicting Muscle Moment Arms for Females and Males.

Plane/Location	Females			Males		
	Regression Equation	R^2	p-value	Regression Equation	R^2	p-value
Lateral/Origin (L_5)						
Sagittal Origin (L_5)						
Lateral/Insertion (L_3)	**-2.35 + 0.437TWXP**	**0.343**	**0.0107**	3.49 + 0.233TWXP	0.129	0.3421
	7.82 + 0.057TWIC	0.010	0.6976	-1.7 + 0.416TWIC	0.261	0.1600
	0.449 + 0.426BMI	**0.481**	**0.0014**	**1.32 + 0.379BMI**	**0.437**	**0.0525**
Sagittal Insertion (L_3)	8.37 - 0.289TDXP	0.119	0.1602	-4.6 + 0.384TDXP	0.277	0.1453
	0.702 + 0.118TDIC	0.029	0.4988	5.74 - 0.064TDIC	0.008	0.8169
	9.25 - 0.295BMI	**0.206**	**0.0586**	-3.76 + 0.313BMI	0.240	0.1812

TDXP = Trunk Depth measured at the Xyphoid Process (cm);
TDIC = Trunk Depth measured at the Iliac Crest (cm);
TWXP = Trunk Depth measured at the Xyphoid Process (cm);
TWIC = Trunk Width measured at the Iliac Crest (cm);
BMI = Body Mass Index (kg/m^2).

Table 1.82. Muscle vector locations for the muscle origins, in the Lateral and A/P Plane for males and females, as a function of anthropometric measurements at the xyphoid process and the iliac crest. Negative values in the lateral plane represent right lateral and positive represent left lateral. Negative values for the A/P plane represent posterior, and positive values represent anterior to the centroid of the vertebral body.

Muscle	Lateral Plane				A/P Plane			
	Female		Male		Female		Male	
	Xyphoid Process	Iliac Crest	Xyphoid Process	Iliac Crest	Xyphoid Process	Iliac Crest	Xyphoid Process	Iliac Crest
RLAT	-0.25	-0.24	-0.26	-0.28	-0.35	-0.33	-0.31	-0.32
LLAT	0.26	0.25	0.26	0.28	-0.43	-0.41	-0.34	-0.35
RES	-0.10	-0.09	-0.09	-0.10	-0.30	-0.28	-0.27	-0.27
LES	0.10	0.10	0.10	0.10	-0.31	-0.29	-0.27	-0.27
RABD	-0.14	-0.14	-0.13	-0.14	0.35	0.33	0.33	0.34
LABD	0.12	0.12	0.10	0.11	0.33	0.31	0.33	0.34
REOB	-0.42	-0.40	-0.39	-0.42	0.31	0.29	0.26	0.26
LEOB	0.40	0.39	0.37	0.40	0.25	0.23	0.25	0.26
RIOB	-0.39	-0.38	-0.35	-0.37	-0.02	-0.01	0.01	0.01
LIOB	0.38	0.37	0.32	0.34	-0.09	-0.07	-0.05	-0.05

Latissimus Dorsi: Projected From T_8 through L_2 to L_5;
Erector Spinae: L_5;
Rectus Abdominis: L_5;
External Obliques: L_4 to L_5 at a 45 degree angle;
Internal Obliques: Projected from L_3 through L_4 to L_5.

Table 1.83. Muscle vector locations for the muscle insertions, in the Lateral and A/P Plane for males and females, as a function of anthropometric measurements at the xyphoid process and the iliac crest. Negative values in the lateral plane represent right lateral and positive represent left lateral. Negative values for the A/P plane represent posterior, and positive values represent anterior to the centroid of the vertebral body.

Muscle	Lateral Plane				A/P Plane			
	Female		Male		Female		Male	
	Xyphoid Process	Iliac Crest	Xyphoid Process	Iliac Crest	Xyphoid Process	Iliac Crest	Xyphoid Process	Iliac Crest
RLAT	-0.49	-0.47	-0.47	-0.51	-0.09	-0.08	-0.08	-0.08
LLAT	0.49	0.47	0.46	0.50	-0.04	-0.04	-0.03	-0.03
RES	-0.10	-0.09	-0.10	-0.10	-0.24	-0.22	-0.23	-0.24
LES	0.10	0.10	0.10	0.11	-0.23	-0.21	-0.21	-0.22
RABD	-0.13	-0.12	-0.14	-0.15	0.52	0.48	0.54	0.56
LABD	0.14	0.13	0.13	0.13	0.53	0.49	0.55	0.57
REOB	-0.40	-0.39	-0.40	-0.43	0.30	0.29	0.29	0.30
LEOB	0.41	0.39	0.39	0.42	0.31	0.29	0.32	0.33
RIOB	-0.36	-0.35	-0.36	-0.38	0.19	0.17	0.15	0.15
LIOB	0.35	0.34	0.34	0.36	0.17	0.15	0.18	0.19

Latissimus Dorsi: T_8;
Erector Spinae: T_8;
Rectus Abdominis: L_1;
External Obliques: L_1;
Internal Obliques: L_3.

Table 1.84. Linear regression equations predicting vertical distance (cm) from the L_5 vertebral level to different muscle vertebral levels in the coronal direction, as a function of standing height.

Vertebral Levels	Females			Males		
	Regression Equation*	R^2	p-value	Regression Equation*	R^2	p-value
T_8 - L_5 (cm)	8.834 + 0.106Height	0.392	0.0032	5.703 + 0.129Height	0.639	0.0055
L_1 - L_5 (cm)	4.734 + 0.053Height	0.261	0.0214	1.759 + 0.072Height	0.580	0.0105
L_3 - L_5 (cm)	3.678 + 0.019Height	0.144	0.0989	0.377 + 0.040Height	0.527	0.0028

* Height is measured in centimeters.

Table 1.85. Mean (s.d.) differences between the largest right and left cross-sectional muscle areas (cm^2), for both male and females, irrespective of vertebral level location. Shaded cells represent significant differences between the right and left sides, at $p \leq 0.05$.

Muscle Group	Females				Males			
	Mean Diff* (s.d.)	Sample Size	% Diff#	p-value	Mean Diff* (s.d.)	Sample Size	% Diff#	p-value
Latissimus Dorsi	152.9 (133.9)	20	13.0	0.0000	216.0 (297.6)	10	10.9	0.0473
Erector Spinae	-28.8 (97.0)	20	-1.6	0.2006	22.9 (100.8)	10	0.8	0.4910
Rectus Abdominis	-15.2 (59.1)	20	-2.7	0.2640	-14.5 (64.8)	10	-1.7	0.4975
External Obliques	47.0 (64.8)	20	6.9	0.0043	-14.9 (122.0)	10	-1.3	0.7085
Internal Obliques	1.5 (81.2)	18	0.3	0.9387	-10.8 (155.7)	9	-1.0	0.8399
Psoas Major	-63.8 (99.1)	20	-6.3	0.0096	-67.7 (124.6)	10	-3.6	0.1199
Quadratus Lumborum	-71.7 (55.8)	19	-19.0	0.0000	-19.8 (77.4)	10	-2.5	0.4465

* Mean difference is calculated as the largest cross-sectional area from the right side minus the left side (cm^2).

Percent difference is calculated as right area minus left area, divided by the right area.

Table 1.86. Analysis of Variance results for the right versus left side cross-sectional muscle area, on a level-by-level basis. Shaded cells represent significant differences of the vertebral level $\times$ side interaction at the $p \leq 0.05$ level.

Muscle	Females	Males
Latissimus Dorsi	0.0001	0.0305
Erector Spinae	0.1669	0.5874
Rectus Abdominis	0.9465	0.3637
External Obliques	0.7518	0.7442
Internal Obliques	0.3156	0.6445
Psoas Major	0.0194	0.5651
Quadratus Lumborum	--	0.5420

Table 1.87. Post-hoc results of Analysis of Variance of right versus left side cross-sectional muscle area (R = right, L = left).

Muscle	Gender	T8	T9	T10	T11	T12	L1	L2	L3	L4	L5	S1
Latissimus Dorsi	Male	R>L	R>L	R>L								
	Female	R>L	R>L	R>L	R>L	R>L						
Psoas	Female									L>R	L>R	

Table 1.88. Difference (mm^2) between female right and left side cross-sectional areas for each muscle group. Percent difference shown in [ ], calculated as right minus left, divided by the left. Statistically significant differences ($p \leq 0.05$) between right and left side cross-sectional areas are indicated by shaded cells.

Muscle	Vertebral Level										
	T_8	T_9	T_{10}	T_{11}	T_{12}	L_1	L_2	L_3	L_4	L_5	S_1
Latissimus Dorsi	151.9 [13.0]	105.1 [10.2]	75.9 [8.5]	63.9 [8.0]	70.4 [10.5]	3.6 [0.7]	-5.3 [-1.5]	-19.1 [-11.5]			
Erector Spinae	-19.3 [-2.5]	-2.5 [-0.3]	-14.8 [-1.5]	-3.1 [0.3]	-7.2 [-0.6]	10.6 [0.8]	23.8 [1.5]	-13.4 [-0.8]	-45.7 [-2.6]	35.1 [3.7]	-1.7 [-0.4]
Rectus Abdominis					-37.8 [-9.3]	-0.5 [-0.1]	-8.7 [-2.4]	-5.0 [-1.3]	-14.8 [-3.0]	-9.0 [-1.9]	-3.5 [0.8]
External Obliques					45.1 [11.7]	45.9 [11.2]	35.3 [7.4]	34.7 [5.7]	19.2 [2.9]	-6.9 [-1.2]	-17.2 [-6.7]
Internal Obliques						32.9 [35.0]	15.0 [6.4]	20.0 [5.5]	-6.4 [-1.1]	-57.3 [-12.0]	-66.5 [-20.9]
Quadratus Lumborum						7.2 [4.2]	9.0 [4.8]	-33.3 [-12.4]	-80.2 [-18.2]	-60.6 [-13.1]	
Psoas Major						-9.2 [-4.6	-15.3 [-4.4]	-9.7 [-1.5]	-49.3 [-5.0]	-66.8 [-7.4]	13.7 [2.2]

Table 1.89. Difference (mm^2) between male right and left side cross-sectional areas for each muscle group. Percent difference shown in [ ], calculated as right minus left, divided by the left. Statistically significant differences ($p \leq 0.05$) between right and left side cross-sectional areas are indicated by shaded cells.

Muscle	Vertebral Level										
	T_8	T_9	T_{10}	T_{11}	T_{12}	L_1	L_2	L_3	L_4	L_5	S_1
Latissimus Dorsi	200.9 [10.2]	192.2 [10.9]	218.0 [14.8]	70.3 [5.1]	105.2 [9.6]	48.5 [5.9]	38.2 [6.4]	-2.5 [-0.9]			
Erector Spinae	-11.3 [-0.9]	-14.0 [-1.0]	-59.9 [-3.8]	-60.6 [-3.4]	-17.6 [-0.9]	1.3 [0.1]	33.2 [1.3]	-0.2 [0.0]	1.6 [0.1]	-54.6 [-3.0]	-39.8 [-4.7]
Rectus Abdominis					-41.7 [-7.9]	-21.5 [-3.9]	-14.8 [-2.9]	-43.4 [-6.5]	23.0 [3.5]	-24.4 [-2.9]	-15.1 [-2.0]
External Obliques					30.0 [6.0]	41.8 [6.6]	3.7 [0.5]	18.1 [2.0]	-10.1 [-0.9]	-68.0 [-8.1]	
Internal Obliques							-64.7 [-21.7]	-11.2 [-1.7]	-31.6 [-3.0]	-41.0 [-6.5]	
Quadratus Lumborum						-14.3 [-5.0]	12.7 [4.2]	-23.9 [-3.8]	-12.2 [-1.8]		
Psoas Major						-60.5 [-18.8]	-101.3 [-12.7]	-49.1 [-3.6]	-55.4 [-3.0]	-39.4 [-2.3]	-25.4 [-2.0]

Table 1.90. Distribution (percentage of total sample, and frequency of occurrence in parenthesis) of the largest muscle area by vertebral level, for the right and left latissimus dorsi.

Vertebral Level	Right Latissimus Dorsi		Left Latissimus Dorsi	
	Female	Male	Female	Male
T_8	95% (19)	90% (9)	90% (18)	70% (7)
T_9	5% (1)	10% (1)	10% (2)	30% (3)

Table 1.91. Distribution (percentage of total sample, and frequency of occurrence in parenthesis) of the largest muscle area by vertebral level, for the right and left erector spinae.

Vertebral Level	Right Erector Spinae		Left Erector Spinae	
	Female	Male	Female	Male
L_2	10% (2)	10% (1)	5% (1)	10% (1)
L_3	45% (9)	50% (5)	45% (9)	50% (5)
L_4	40% (8)	40% (4)	50% (10)	40% (4)
L_5	5% (1)	--	--	--

Table 1.92. Distribution (percentage of total sample, and frequency of occurrence in parenthesis) of the largest muscle area by vertebral level, for the right and left rectus abdominis.

Vertebral Level	Right Rectus Abdominis		Left Rectus Abdominis	
	Female	Male	Female	Male
T_{12}	--	--	5% (1)	--
L_1	--	10% (1)	5% (1)	--
L_2	10% (2)	--	5% (1)	--
L_3	5% (1)	--	5% (1)	10% (1)
L_4	40% (8)	10% (1)	35% (7)	--
L_5	20% (4)	70% (7)	30% (6)	70% (7)
S_1	25% (5)	10% (1)	15% (3)	20% (2)

Table 1.93. Distribution (percentage of total sample, and frequency of occurrence in parenthesis) of the largest muscle area by vertebral level, for the right and left external obliques.

Vertebral Level	Right External Oblique		Left External Oblique	
	Female	Male	Female	Male
L_2	5% (1)	--	5% (1)	--
L_3	30% (6)	10% (1)	10% (2)	10% (1)
L_4	60% (12)	80% (8)	80% (16)	70% (7)
L_5	5% (1)	10% (1)	5% (1)	20% (2)

Table 1.94. Distribution (percentage of total sample, and frequency of occurrence in parenthesis) of the largest muscle area by vertebral level, for the right and left internal obliques.

Vertebral Level	Right Internal Oblique		Left Internal Oblique	
	Female	Male	Female	Male
L_3	16.7% (3)	10% (1)	11.1% (2)	11.1% (1)
L_4	83.3% (15)	80% (8)	88.9% (16)	77.8% (7)
L_5	--	10% (1)	--	11.1% (1)

Table 1.95. Distribution (percentage of total sample, and frequency of occurrence in parenthesis) of the largest muscle area by vertebral level, for the right and left quadratus lumborum.

Vertebral Level	Right Quadratus Lumborum		Left Quadratus Lumborum	
	Female	Male	Female	Male
L_2	5.3% (1)	--	--	--
L_3	15.8% (3)	10% (1)	10% (2)	10% (1)
L_4	73.7% (14)	90% (9)	85% (17)	90% (9)
L_5	5.3% (1)	--	5% (1)	--

Table 1.96. Distribution (percentage of total sample, and frequency of occurrence in parenthesis) of the largest muscle area by vertebral level, for the right and left psoas major.

Vertebral Level	Right Psoas Major		Left Psoas Major	
	Female	Male	Female	Male
L_4	85% (17)	80% (8)	60% (12)	60% (6)
L_5	15% (3)	20% (2)	40% (8)	40% (4)

Part 2: Physiological measurement of the in-vivo muscular length-strength and force-velocity relationships in the female trunk torso.

Introduction

The estimation of moments and forces about the lower back using the EMG-assisted biomechanical model consists of adding the predicted muscle forces in three dimensions, and then using muscle moment-arm relationships, adding and partitioning the resulting moment in three dimensions. The determination of muscle force, however, is a function of muscle dynamics, which affect the EMG signal and the force output, and the force producing capability of the muscle, which includes the gain and the size of the muscle. The muscle areas and geometry (e.g., location of the vector coordinates for insertion and origins) relationships for the female were determined in Part 1. The muscle gains should remain constant in an individual. The force output of a muscle however, depends on the length of the muscle and the velocity of contraction at any point in time during the exertion. These factors also affect the EMG activity elicited from the muscle. Thus, in order to develop a valid dynamic biomechanical EMG-assisted model to estimate spinal loading, the muscle length-strength and force-velocity relationships must be determined.

Background and Objectives

The objective of Part 2 was to develop the empirical muscle length-strength and muscle force-velocity relationships that describe the dynamic muscle behavior of military age females, which then will be incorporated into a female specific dynamic EMG-assisted biomechanical model. Past research has found that the length of the muscle and the velocity of the muscle contraction have an affect on the maximum muscle force capabilities, as well as the electromyographic activity elicited from the muscles (Bigland and Lippold, 1954; Hill, 1938; Komi, 1973; Raschke and Chaffin, 1996; Wilkie, 1950). Additionally, these relationships have been developed on muscle activities from males. Thus, in order to permit accurate assessments of spinal loading and associated LBD risk of females performing *dynamic* material handling tasks, it is necessary to generate the physiologic description of muscle dynamics that accurately describes military age women.

Administrative Note

In the accepted research proposal, the experimental design and methods for Part 2 called for collecting the electromyographic, kinetic and kinematic data from 35 females in a Free Dynamic mode. After the 35 subjects had been collected, seven subjects had to be excluded from the dataset of 35 females due to equipment malfunctions, which were found during quality control checks of the collected data. Efforts continue to collect the agreed upon 35 subjects for this part of the research.

The Free Dynamic mode of lifting allows the subjects to lift the weights at different controlled isokinetic trunk velocities while their body was unconstrained, except for their feet. Preliminary analyses from these Free Dynamic lifting trials did not result in acceptable model performances, with low r^2's and high gain values. Thus, it was hypothesized that the subjects were allowing their hips and pelvis's to rotate during the lifting motions, thus resulting in highly variable length-strength and force-velocity results. Therefore, to remove the potential confounding effect of the rotation of the pelvis and hips, additional subjects were collected in a device called a pelvic support structure, which restricted movement to the trunk only, and not the pelvis. Sixteen subjects have been collected in the PSS, and the modulation factors determined from this new dataset are very promising as the performance of the biomechanical model using these modulations have enhanced the performance parameters far above those from that based on the Free Dynamic data. Similarly, when the modulation factors determined from the PSS were applied to the data from the Free Dynamic exertions, the biomechanical model performance parameters were again more acceptable than those when the modulation factors were determined from the Free Dynamic exertions. Thus, the approach currently being used is to determine the length-strength and force-velocity relationships that we know are valid (from the PSS lifting trials), and apply these relationships to the Free Dynamic lifting exertions, and make the appropriate modifications. Additional subjects are currently being recruited and run through the experimental protocol in the PSS, as well as to complete the agreed upon sample size for the Free-Dynamic lifting protocol. It is felt that the collection of the additional subjects will solidify the female length-strength and force-velocity modulation factors, and will produce acceptable results when applied to the Free Dynamic exertions.

Thus, the results reported as of October 24, 1997, for Part 2 include 1) the derivation of the female length-strength and force-velocity modulation factors from 16 female subjects performing lifting exertions while constrained at the hips, and 2) the application of these modulation factors to the kinematic, kinetic, and electromyographic data collected from the 28 subjects in the free-dynamic mode to assess the model performance during controlled sagittally symmetric free-dynamic lifting. The results presented are promising, and it is expected that the additional subjects to be collected to finish out this phase will confirm the expected relationships.

Methods

Subjects

The subjects consisted of 16 females for the lifting performed while constrained at the hips (in a pelvic support structure, described later), and 28 females for the free-dynamic lifts, all recruited from the local community. The anthropometric measurements for subjects in both lifting modes are shown in Table 2.1 None of the subjects were experiencing any low back pain at the time of the testing.

Table 2.1 Anthropometric data from the female subjects for the lifting in the pelvic support structure and from the free dynamic lifts.

Anthropometric Variable	Pelvic Support Structure (N=16)	Free Dynamic (N=28)
Age (yrs)	24.7 (6.5)	25.0 (6.3)
Standing Height (cm)	166.5 (7.3)	167.6 (5.2)
Weight (kg)	62.5 (9.5)	61.2 (8.3)
Trunk Width at Iliac Crest (cm)	27.9 (1.9)	27.2 (2.2)
Trunk Depth at Iliac Crest (cm)	19.2 (2.1)	18.8 (2.1)
Trunk Width at Xyphoid Process (cm)	27.1 (1.1)	27.6 (1.3)
Trunk Depth at Xyphoid Process (cm)	20.0 (2.0)	19.7 (1.9)
Body Mass Index (kg/m^2)	22.5 (2.5)	21.7 (2.1)

Experimental Design

The experimental design described below applies to both the data collected from the free-dynamic mode as well as the lifting with the hips constrained. The dependent variable consisted of the normalized electromyographic (EMG) activity from each of ten trunk muscles. The independent variables consisted of the weight of lift (15 lb. or 30 lb.), speed of the lifting motion (15, 30, 45, and 60 degrees per second) through a range of 50 degrees forward flexion to an upright standing position, as well as a static holding position (0 deg/sec) at forward trunk flexion angles of 5, 20, 35, and 50 degrees. The various weight and velocity lifting conditions were presented to each subject in a random order.

Equipment

A lumbar motion monitor (LMM), which is essentially an exoskeleton of the spine, was used to collect the kinematic trunk variables (Marras et al., 1992). The LMM was placed on the subjects back, and provided feedback via a computer screen as to when the subject reached the starting trunk angle. The LMM also measured and provided feedback on the trunk extension velocity, as the subject viewed the trunk velocity trace and their performance on a computer screen.

Electromyographic (EMG) activity was collected through the use of bipolar silver-silver chloride surface electrodes, spaced approximately 3 cm apart over the ten trunk muscles (Mirka and Marras, 1993). The ten trunk muscles included the right and left pairs of the latissimus dorsi, erector spinae, rectus abdominis, external obliques, and the internal obliques. The subjects performed the lifting exertions while standing on a forceplate (Bertec 4060A, Worthington, OH), which measured the three dimensional ground reaction moments and forces generated during the lifting exertions.

While the LMM, electromyography, and a forceplate were used for both segments of this study (i.e., the lifting performed with the hips constrained and also for the free-dynamic mode), the external structures were different between the two modes. For the free-dynamic conditions, the subjects were not constrained in any way except for the requirement that they keep their feet on the forceplate during the lifting exertion. To translate the moments and forces measured from the forceplate to the estimated location of the L_5/S_1 intervertebral disc, the location and orientation of the subjects' lumbosacral joint was monitored by use of a *sacral location orientation monitor* (SLOM) and a *pelvic orientation monitor* (POM, see Figure 2.1), (Fathallah et al., 1997). For lifting trials performed with the hips constrained, the subjects were positioned into a *pelvic support structure* (PSS) that was attached to the forceplate. The PSS restrained the subject's pelvis and hips in a fixed position (see Figure 2.2). The position of the L_5/S_1 relative to the center of the forceplate remained constant then for all lifting trials, which allowed the forces and moments measured by the forceplate to be rotated and translated to the position of the L_5/S_1 (Granata et al., 1995).

All data signals from the above equipment were collected simultaneously through customized Windows™ based software developed in-house. The signals were collected at 100 Hz and recorded on a 486 computer via an analog-to-digital conversion board and stored for later analysis.

To allow the subjects to control their lifting velocity in an isokinetic manner, an additional computer was used to display the instantaneous velocity recorded by the LMM in real time. The signal was transferred from the LMM to the computer through an analog-to-digital board and converted into velocity by customized software. The subjects were then to control their isokinetic lifting velocity by keeping the trace of the velocity within tolerance lines displayed on the computer.

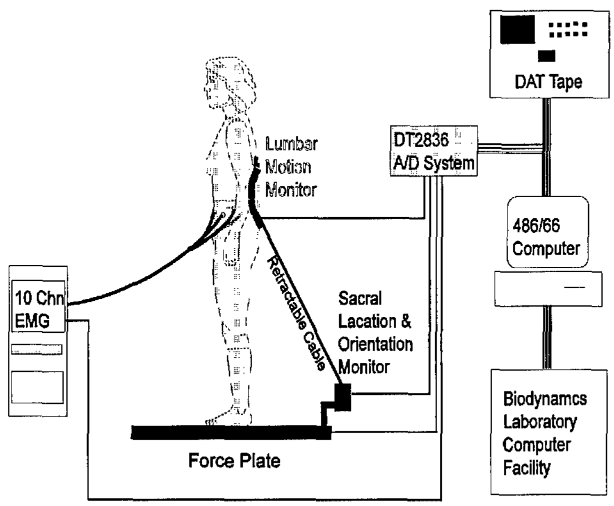

Figure 2.1. Experimental equipment for the Free Dynamic lifting conditions.

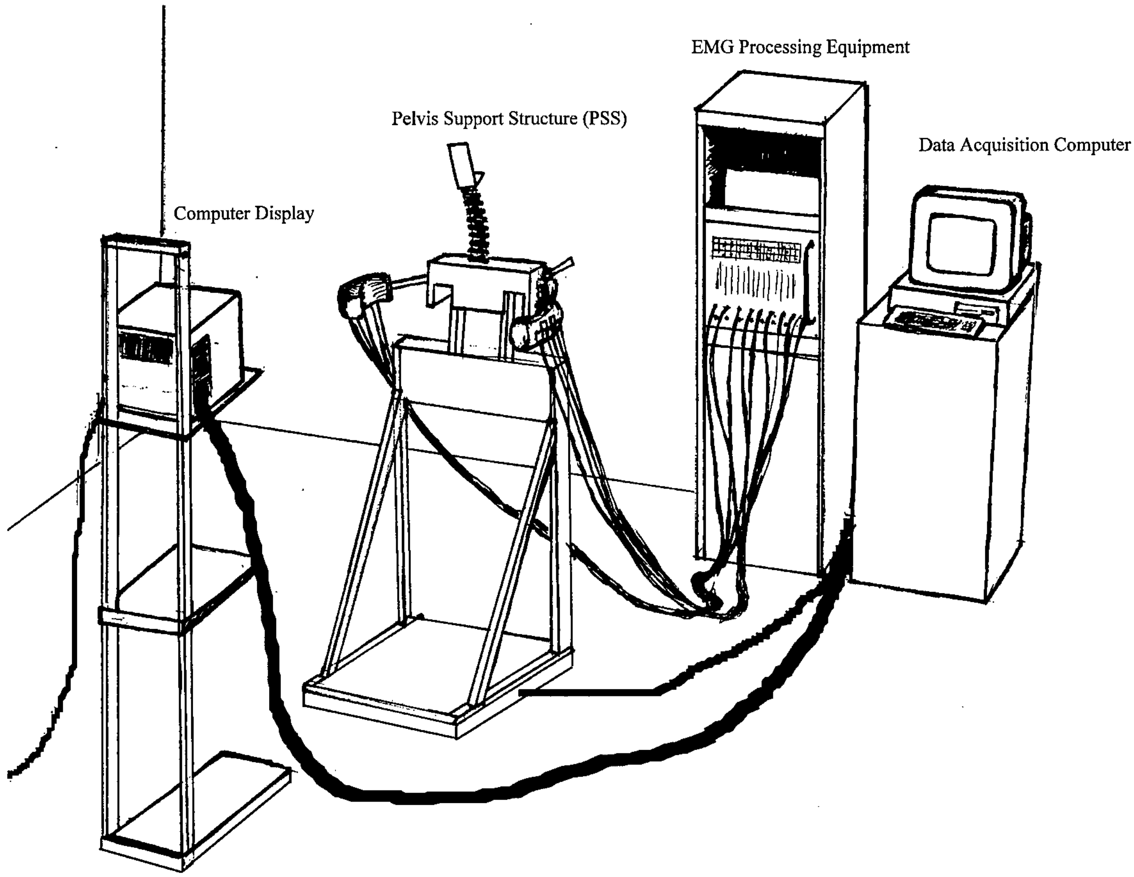

Figure 2.2. Experimental equipment for the lifting trials using the Pelvic Support Structure.

Experimental Procedures

Upon the subjects arrival to the testing laboratory, the subjects read and signed a consent form, and took a pregnancy test so as to determine their pregnancy status. Once they were determined not to be pregnant, anthropometric data and demographic information were obtained. The surface electrodes for the EMG were then applied over each of ten trunk muscles, while skin impedances were kept below 500 kΩ. Maximum voluntary contractions (MVCs) for each of the trunk muscles were obtained, with the subjects performing MVCs for trunk extension and flexion static exertions, as well as right and left twisting and right and left lateral bending, all against a constant resistance. All resulting trunk muscle EMG data obtained from the experimental trials were then normalized to the maximum EMG activity obtained during these six directional MVCs.

Thus, the normalized EMG activity represents the fraction of maximum muscle activity that is applied at any point in time, and also allows relative muscle activity comparisons across subjects as well as within subjects. Following the MVCs, an LMM was placed on the subject's back, and the subject was then allowed to practice the lifting motion to become proficient with the different controlled trunk velocities. The experimental task required the subjects to control and maintain their trunk lifting velocity between tolerance limits (displayed on a computer screen) for each of the different velocity conditions. If the subject failed to maintain the trunk motion within the tolerance limits, the trial was rerun. A three percent tolerance was used by displaying two lines that were 1.5 percent above and below the target velocity.

Modulation Factor Determination

The determination of the muscle length-strength and force-velocity modulation factors consisted of a biomechanical analysis of the normalized EMG data collected from the subjects in the PSS. This was accomplished by comparing the measured sagittal trunk moment from the forceplate with the un-modulated (i.e., without the muscle length-strength and muscle force-velocity relationships) predicted sagittal trunk moment (Granata and Marras, 1995; Granata, 1993). Specifically, this included a systematic analysis procedure incorporating different inputs into an EMG-assisted biomechanical model using the general form of equations 2.1 and 2.2 (Marras and Sommerich, 1991a, 1991b; Granata and Marras, 1993; Marras and Granata, 1995; Granata and Marras, 1995; Marras and Granata, 1997). This method then minimized the average variation of the ratio of external to internal sagittal moment as a function of muscle length and velocity. Additionally, a simplifying assumption was made that the erector spinae group are the sole muscles that counteract the external moment during the sagittally symmetric lifting exertions. This assumption seemed reasonable as antagonistic muscle activity was shown to be minimal during similar motions of other studies (Granata and Marras, 1995; Davis et al., in press).

$$\text{Force}_j = \text{Gain} \times (\text{EMG}_t / \text{EMG}_{max}) \times \text{Area}_j \times f(\text{Vel}) \times f(\text{Length}) \qquad (Eq\ 2.1)$$

$$M_{x\text{-pred}} = \Sigma r_j \times \text{Force}_j \qquad (Eq\ 2.2)$$

where:

Force_j = tensile force for muscle j;
Gain = physiological muscle stress (N/cm^2);
EMG_t = integrated EMG from the lifting exertion;
EMG_{max} = integrated EMG from MVCs;
Area_j = Maximum cross-sectional area of muscle j;
f(Vel) = the muscle force-velocity modulation factor;
f(Length) = the muscle length-strength modulation factor;
$M_{x\text{-pred}}$ = Predicted sagittal trunk moment during the lifting exertion;
r_j = moment-arm for muscle j.

Initially, the data for the dynamic lifting exertions were restricted to the range of 0 degrees to 40 degrees sagittal flexion, as the passive structures of the lower back are estimated to begin sharing the loading at increasing rates at sagittal flexion angles greater than 45 degrees (McGill et al., 1986; Kirking, 1997). Thus, restricting the range of dynamic exertion data to less than 40 degrees sagittal flexion ensures that the active structures (e.g., muscles) are fully contributing to the spinal loading. The exertions from each subject were run through the EMG-assisted model without any modulation factors (i.e., without Gain, f[Vel] and f[Length]) to determine the subject specific average gain value. Next, the average gain per subject was input into the biomechanical model, and all the exertions were modeled again using the unmodulated versions of equations 2.1 and 2.2 (i.e., without the f[Vel] and f[Length] factors). The measured sagittal moment from the forceplate ($M_{x\text{-meas}}$) was then compared with the predicted sagittal moment ($M_{x\text{-pred}}$) at each point in time, to obtain a vector of the ratio of $M_{x\text{-meas}}$ divided by $M_{x\text{-pred}}$. This vector of the moment ratio was then used as the dependent variable in a multiple linear regression model to predict the moment ratio as a function of the muscle length for the erector spinae. Specifically, the form of the multiple linear regression model was:

$$Y = \beta_0 + \beta_1(\text{Length}) + \beta_2(\text{Length}^2) + \beta_3(\text{Length}^3) \qquad \textit{(Eq. 2.3)}$$

where:

Y = ratio of measured sagittal moment ($M_{x\text{-meas}}$) and predicted sagittal moment ($M_{x\text{-pred}}$);
Length = Muscle length expressed as a ratio of estimated muscle length divided by the resting muscle length.

The resulting regression equation consisting of the β_0, β_1, β_2 and β_3 coefficients for muscle length factor was then used as the muscle length-strength modulation factor. The length-strength modulation factor was then input into equations 2.1 and 2.2, and the EMG-assisted biomechanical model was then run again without the muscle force-velocity modulation factor [f(Vel)] to identify the force-velocity effects. The measured sagittal moment from the forceplate was again compared with the predicted sagittal moment at each point in time to obtain a vector of the ratio of $M_{x\text{-meas}}$ divided by $M_{x\text{-pred}}$. This vector of the moment ratio was then used as the dependent variable in a linear regression model, to predict this moment ratio as a function of the erector spinae muscle velocity. Specifically, the form of the multiple regression model was:

$$Y = \beta_0 + \beta_1(\text{Vel}) \qquad \textit{(Eq. 2.4)}$$

where:

Y = ratio of measured sagittal moment ($M_{x\text{-meas}}$) and predicted sagittal moment ($M_{x\text{-pred}}$);
Vel = Muscle velocity expressed as a ratio ≤ 1.0, where a static condition results in a ratio of 1.0, with increasing velocities having smaller ratios.

The resulting beta coefficients (β_0 and β_1) for the muscle velocity factor was then used as the muscle force-velocity modulation factor in Equation 2.1, which is used to determine the instantaneous muscle force.

Development of Female Specific Biomechanical Model

Since the EMG-assisted model is an interactive system, a systematic procedure was necessary to determine which combinations of muscle vector locations and cross-sectional areas result in the best estimates of the modulation factors for muscle length-strength and muscle force-velocity. A step-by-step approach was used to assess any improvements or decrements in model performance indices as the cross-sectional muscle areas, muscle vector orientations, and length-strength and force-velocity parameters were varied. As shown in Table 2.2, a five-step model building procedure was performed, varying only one variable at a time. In order to establish a benchmark against which model performance could be judged, Model 1 was built using the male EMG-assisted biomechanical model, with the regression equations predicting the maximum cross-sectional muscle areas from the body mass index (BMI) (Tables 1.65 to 1.69 from Part 1) as well as the muscle vector locations at the origin and insertion points and the length-strength and force-velocity modulation factors, all based on male data (Granata and Marras, 1993; Marras and Granata, 1995, 1997). Model 2 used the length-strength and force-velocity modulation factors determined from the female lifting exertions performed in the PSS, with all other model parameters based on male data (i.e., muscle cross-sectional areas and muscle vector locations). Model 3 used the regression equations for the largest cross-sectional muscle areas based on the BMI for the females from Part 1 (Tables 1.64 to 1.68) along with the female length-strength and force-velocity modulations, with the muscle vector locations based on the male model. Model 4 used the new coefficients for estimation of the muscle vector locations at the origin and insertion levels for females from Table 1.82 and 1.83 from Part 1 based on measurements about the iliac crest, which included the external obliques projected at a 45 degree caudal and anterior angle, as well as the previously described parameters from the female data. Finally, Model 5 used the new female coefficients for the muscle vector locations which include the locations without projecting the external obliques at a 45 degree anterior and caudal angle in the sagittal plane as well as the previously described variables. Except for Model 1 where the female EMG, kinetic and kinematic data were applied to an existing male biomechanical model with already determined male length-strength and force-velocity modulation factors, the length-strength and force-velocity modulation determination procedures were applied individually for each of the models. Thus, in theory, the modulation factors will vary between the different models depending upon the differences in the prediction of the other factors (e.g., gain, cross-sectional area). Although the BMI was used in this study period to predict the female cross-sectional muscle areas, results from Part 1 indicate that measures about the xyphoid process of the female trunk were just as effective in predicting the largest muscle cross-sectional areas. Therefore, efforts are continuing to investigate the use of the xyphoid process measurements, and their effect on length-strength and force-velocity modulation and biomechanical model performance.

To determine the validity of the new length-strength and force-velocity modulation factors, the performance of each of the five models was examined by comparing the predicted and measured moment profiles and quantitatively determined by means of a statistical squared correlation (r^2), the average absolute error (AAE) of the comparison, along with the existence of a physiologically valid muscle gain. The value of the r^2 indicates how well the measured and predicted sagittal moment variability coincide. The AAE indicates the magnitude of the difference between the predicted and measured sagittal moments. For gain values to be physiologically valid, the predicted gain values must lie between 30 and 100 $N{\cdot}cm^{-2}$ (McGill et al, 1988; Reid and Costigan, 1987; Weis-Fogh and Alexander, 1977). Thus, a high r^2 value, combined with low AAEs and physiologically valid gain values implies that the inputs into the model accounts for the variability of the lifting moment.

Table 2.2. Data sources for maximum cross-sectional muscle areas and muscle vector locations for different biomechanical models used to assess the muscle length-strength (L-S) and force-velocity (F-V) modulation factors.

Model	Cross-Sectional Areas		L-S and F-V Modulation Factors		Muscle Vector Locations		
	Male (BMI)*	Female (BMI)*	Male#	Female	Male#	Hybrid	Female
1	X		X		X		
2	X			X	X		
3		X		X	X		
4		X		X		X	
5		X		X			X

* Cross-sectional muscle areas for both males and females determined from regression equations in Tables 1.64-1.68, based upon the body mass index (kg/m^2).

Length-strength (L-S) and force-velocity (F-V) modulation factors for the males from Granata and Marras (1995).

Statistical Analysis

The objectives of the research of Part 2 were to 1) investigate how the muscles responsible for spinal loading respond to different conditions such as velocity and weight of lift, and 2) document how the biomechanical models with different parameters behave under these different conditions. Therefore, the normalized muscle activity as a function of the different conditions were documented, as well as the magnitudes and changes of the biomechanical performance parameters as a function of the different inputs.

First, descriptive statistics on all the dependent variables, consisting of the mean and standard deviation were first determined, for both the PSS and Free Dynamic portions of this study. Next, the normalized EMG data were analyzed to assess the effects of different task parameters on the resulting normalized EMG values, again for both the PSS and Free Dynamic portions of the study. Multivariate Analysis of Variance (MANOVA) and ANOVA techniques were used to assess the effects of the task parameters, using a repeated measures approach since multiple observations were taken from the same subjects. The dependent variable consisted of the normalized EMG value from each of the ten trunk muscles at the time of the maximum sagittal moment during each of the lifting exertions. Analysis of Variance was performed for each of the 10 muscles for the independent variables which were significant in the MANOVA. Post-hoc test included Tukey pair-wise comparisons. Significance was judged relative to an α value of 0.05.

Results

Mean Normalized Muscle Activity

The descriptive statistics for the mean (s.d.) sagittal moment and normalized muscle activity for lifting trials performed in the PSS are shown in Table 2.3, whereas the sagittal moment and normalized muscle activity statistics from the Free Dynamic lifting trials are shown in Table 2.4. Generally, the greatest muscle activity across all velocities and weights occurred in the trunk extensor muscles, with the erector spinae muscles resulting in a large amount of normalized activity, and smaller levels of activity present in the internal obliques. This trend was true for both the PSS and Free Dynamic modes. The sagittal moment remained relatively constant across all velocity and weight conditions, for the PSS lifting trials, however, the range was larger for the Free Dynamic trials. A consistent trend also existed when comparing the magnitudes of the dependent variables between the two experimental modes (PSS vs. Free Dynamic) in that the sagittal moments and the normalized muscle activity for the erector spinae and internal obliques were consistent higher for all velocity and weight conditions for the Free Dynamic lifting trials when compared to the moments and normalized activity from the PSS lifting trials.

The results of the MANOVA on the mean normalized muscle activity as a function of the task parameters is shown in Table 2.5 for the PSS lifting trials, and for the Free Dynamic lifting trials in Table 2.6. For both experimental modes, there was a significant effect on the collective muscle activity from the weight and velocity effects, but no significant effect of the weight by velocity interaction. Thus, ANOVA was run independently for each muscle while reporting only the main effects of velocity and weight.

Table 2.3. Descriptive results for the mean (s.d.) normalized muscle activity (percent of maximum muscle activity) and maximum sagittal moment (Nm) as a function of velocity and weight, for lifting trials performed in the ***Pelvic Support Structure***.

Variable	Velocity (deg/s)					Weight# (lbs)	
	0*	15	30	45	60	15	30
Sagittal Moment	58.0 (14.3)	63.3 (15.6)	66.2 (15.9)	64.5 (15.1)	66.1 (16.9)	61.1 (13.9)	69.0 (16.5)
RLAT	0.05 (0.04)	0.07 (0.04)	0.08 (0.04)	0.08 (0.05)	0.08 (0.05)	0.06 (0.04)	0.09 (0.05)
LLAT	0.05 (0.03)	0.06 (0.03)	0.07 (0.03)	0.07 (0.04)	0.08 (0.05)	0.06 (0.03)	0.08 (0.04)
RES	0.30 (0.09)	0.55 (0.18)	0.62 (0.21)	0.70 (0.22)	0.71 (0.19)	0.58 (0.21)	0.71 (0.19)
LES	0.26 (0.10)	0.48 (0.17)	0.56 (0.27)	0.63 (0.30)	0.66 (0.28)	0.52 (0.25)	0.64 (0.27)
RABD	0.09 (0.13)	0.08 (0.05)	0.08 (0.05)	0.10 (0.06)	0.10 (0.07)	0.09 (0.05)	0.09 (0.06)
LABD	0.06 (0.05)	0.08 (0.06)	0.08 (0.07)	0.09 (0.08)	0.10 (0.08)	0.08 (0.07)	0.09 (0.08)
REOB	0.06 (0.04)	0.07 (0.05)	0.08 (0.05)	0.08 (0.05)	0.08 (0.05)	0.08 (0.05)	0.08 (0.05)
LEOB	0.05 (0.02)	0.07 (0.05)	0.06 (0.03)	0.07 (0.03)	0.09 (0.13)	0.08 (0.10)	0.07 (0.04)
RIOB	0.08 (0.03)	0.15 (0.08)	0.16 (0.09)	0.18 (0.09)	0.19 (0.10)	0.15 (0.09)	0.19 (0.09)
LIOB	0.09 (0.03)	0.15 (0.06)	0.15 (0.06)	0.19 (0.09)	0.19 (0.08)	0.15 (0.07)	0.19 (0.08)

* The velocity condition of 0.0 deg/sec was at the 35 degree forward trunk flexion angle, which was the angle of the maximum sagittal moment.
# The weight conditions only include data from the dynamic lifting trials.

Table 2.4. Descriptive results for the mean (s.d.) normalized muscle activity (percent of maximum muscle activity) and maximum sagittal moment (Nm) as a function of velocity and weight, for lifting trials performed in the ***Free Dynamic*** mode.

Variable	Velocity (deg/s)					Weight# (lbs)	
	0*	15	30	45	60	15	30
Sagittal Moment	100.9 (30.0)	91.8 (29.3)	92.3 (30.6)	93.6 (28.2)	93.8 (26.7)	82.7 (24.5)	103.0 (28.8)
RLAT	0.08 (0.05)	0.08 (0.06)	0.08 (0.06)	0.09 (0.10)	0.11 (0.10)	0.08 (0.08)	0.10 (0.09)
LLAT	0.09 (0.06)	0.09 (0.07)	0.08 (0.08)	0.10 (0.10)	0.12 (0.13)	0.08 (0.07)	0.12 (0.11)
RES	0.38 (0.17)	0.61 (0.33)	0.66 (0.32)	0.74 (0.35)	0.76 (0.39)	0.62 (0.30)	0.76 (0.38)
LES	0.38 (0.21)	0.59 (0.30)	0.68 (0.36)	0.76 (0.38)	0.78 (0.43)	0.63 (0.33)	0.77 (0.40)
RABD	0.05 (0.04)	0.07 (0.11)	0.10 (0.21)	0.08 (0.14)	0.11 (0.25)	0.09 (0.18)	0.09 (0.19)
LABD	0.06 (0.06)	0.07 (0.06)	0.08 (0.08)	0.09 (0.08)	0.09 (0.10)	0.08 (0.08)	0.08 (0.08)
REOB	0.05 (0.04)	0.06 (0.05)	0.07 (0.07)	0.07 (0.09)	0.08 (0.11)	0.07 (0.09)	0.07 (0.07)
LEOB	0.05 (0.05)	0.07 (0.05)	0.07 (0.06)	0.08 (0.10)	0.08 (0.10)	0.07 (0.08)	0.08 (0.08)
RIOB	0.14 (0.10)	0.24 (0.19)	0.26 (0.22)	0.28 (0.24)	0.30 (0.25)	0.24 (0.21)	0.29 (0.24)
LIOB	0.14 (0.06)	0.22 (0.12)	0.24 (0.13)	0.27 (0.17)	0.29 (0.15)	0.22 (0.12)	0.29 (0.16)

* The velocity condition of 0.0 deg/sec was at the 35 degree forward trunk flexion angle, which was the angle of the maximum sagittal moment.

The weight conditions only include data from the dynamic lifting trials.

Table 2.5. MANOVA and ANOVA results for the normalized muscle activity for the effects of velocity, weight, and the velocity by weight interaction, for lifting trials performed in the Pelvic Support Structure. Shaded cells represent significant effects ($p \leq 0.05$).

MANOVA	Velocity	Weight	Velocity × Weight
	p=0.0049	p=0.0149	p=0.5905
Muscle			
R. Latissimus Dorsi	p=0.0800	p=0.0019	
L. Latissimus Dorsi	p=0.0135	p=0.0009	
R. Erector Spinae	p≤0.0001	p≤0.0001	
L. Erector Spinae	p≤0.0001	p≤0.0001	
R. Rectus Abdominis	p=0.0070	p=0.2362	
L. Rectus Abdominis	p=0.1739	p=0.0179	
R. External Oblique	p=0.1493	p=0.0537	
L. External Oblique	p=0.4459	p=0.7097	
R. Internal Oblique	p≤0.0001	p≤0.0001	
L. Internal Oblique	p≤0.0001	p=0.0004	

Table 2.6. MANOVA and ANOVA results for the normalized muscle activity for the effects of velocity, weight, and the velocity by weight interaction, for lifting exertions performed in the Free Dynamic mode. Shaded cells represent significant effects ($p \leq 0.05$).

MANOVA	Velocity	Weight	Velocity × Weight
	p≤0.0001	p≤0.0001	p=0.6342
Muscle			
R. Latissimus Dorsi	p=0.0136	p=0.2038	
L. Latissimus Dorsi	p=0.0058	p=0.0009	
R. Erector Spinae	p≤0.0001	p≤0.0001	
L. Erector Spinae	p≤0.0001	p≤0.0001	
R. Rectus Abdominis	p=0.1910	p=0.1536	
L. Rectus Abdominis	p=0.0004	p=0.5574	
R. External Oblique	p=0.0615	p=0.7636	
L. External Oblique	p=0.0874	p=0.1752	
R. Internal Oblique	p≤0.0001	p≤0.0001	
L. Internal Oblique	p≤0.0001	p≤0.0001	

The ANOVA results for the PSS lifting trials generally found that there were significant effects of weight for all but the right rectus abdominis, and both sides of the external obliques. The velocity of lifting had significant effects on all but the right latissimus dorsi, left rectus abdominis, and both sides of the external obliques. The results for the Free Dynamic lifting trials were very similar, with weight not having a significant effect for either the rectus abdominis, external obliques, nor the right latissimus dorsi. Only the external obliques and right rectus abdominis did not vary significantly with velocity of lifting. Consistent trends existed when considering the post-hoc tests on the significant effects across all the muscles. Where there were significant differences in muscle activity due to the weight effect (see Tables 2.5 and 2.6), post-hoc tests found that that the 30 lb. condition always resulted in statistically significant greater muscle activity than the 15 lb. condition, for both the ***PSS*** (Table 2.3) and ***Free Dynamic*** (Table 2.4) portions of the study. Inspection of the magnitude of the differences, however, reveals that except for the erector spinae muscles, the difference of the muscle activities between the 15 and 30 lb. conditions was very small (Tables 2.3 and 2.4). For the muscles that resulted in statistically significant different muscle activity as a function of lifting velocity, in every case, the 60 degree/sec velocity condition resulted in higher normalized muscle activity than the 15 degree/sec velocity condition for the lifting trials in the ***PSS***, with the 60 degree/sec velocity condition also resulting in greater muscle activity than the 30 degree/sec condition for the extensors (erector spinae and internal obliques). The magnitudes of the difference, however, were very small for all muscles except for the erector spinae (Table 2.3). Similar trends existed for the muscles with significant differences in normalized activity as a function of velocity for the lifting trials during the ***Free Dynamic*** mode (Table 2.4). The 60 deg/sec velocity condition resulted in statistically significant greater normalized muscle activity than the 15 deg/sec and 30 deg/sec conditions for the erector spinae and internal obliques, and the 60 deg/sec resulted in significantly greater right left latissimus dorsi normalized muscle activity than the 30 deg/sec condition. Once again, inspecting the magnitude of the differences, marginal differences in muscle activity as a function of the velocity conditions existed for all significant muscles except the erector spinae and internal obliques (Table 2.4).

Model Parameters

The model performance results from systematic analysis of the inputs into the force and moment equations (Eq. 2.1 and 2.2) for the prediction of the sagittal moment are shown in Table 2.7. For each model, the data collected from the PSS were used to develop the length-strength and force-velocity modulation factors, from 12 subjects. These modulation factors were then applied to the data from the 28 subjects collected in the Fee Dynamic mode, thus allowing comparison of model performance parameters between the different lifting modes (PSS vs. Free Dynamic) within each model, as well as across models. The use of only the dynamic lifting trials resulted in better model parameters (lower gains and higher r^2's) than when using both the static and dynamic trials. This is expected since the static exertions do not induce a *change* in the moment, which is what is tracked by the r^2 statistic. The two models which resulted in good model performance parameters included Models' 1 and 3, using the dynamic lifting trials (shaded cells in Table 2.7). Using the male only model and applying the female kinematic, kinetic, and EMG data (Model 1), the mean and median r^2's were very acceptable (0.91 and 0.95, respectively), however, the mean and median muscle gains (86.0 and 83.3 $N{\cdot}cm^{-2}$) were on the high end of the valid range. When the female cross-sectional areas and female length-strength and force-velocity modulation factors were used, the r^2's and AAE's remained virtually unchanged, and the muscle gains dropped to a mean of 32.9 $N{\cdot}cm^{-2}$ and represent values that are physiologically reasonable. Thus, this combination of muscle areas, modulation factors resulted in very good model performance, as the distribution of the r^2's shows both a high mean and median (Figure 2.3). The length-strength and force-velocity modulation factors determined from the PSS lifting trials were applied to the data from the Free Dynamic lifting trials. This resulted in higher but still valid gains (mean=60.8 $N{\cdot}cm^{-2}$), and still respectable mean and median r^2 values (0.81 and 0.87, respectively), where its distribution can be found in Figure 2.4.

Since Model 3 resulted in the best model performance parameters, model performance parameters were updated by including the data from four additional subjects in the PSS (N=16), where the resulting modulation factors were then applied to the data from the Free Dynamic lifting trials. As shown in Table 2.8, the model performance parameters (i.e., gain, r^2, AAE) remained virtually unchanged from the results of Model 3 in Table 2.7, based on four fewer subjects.

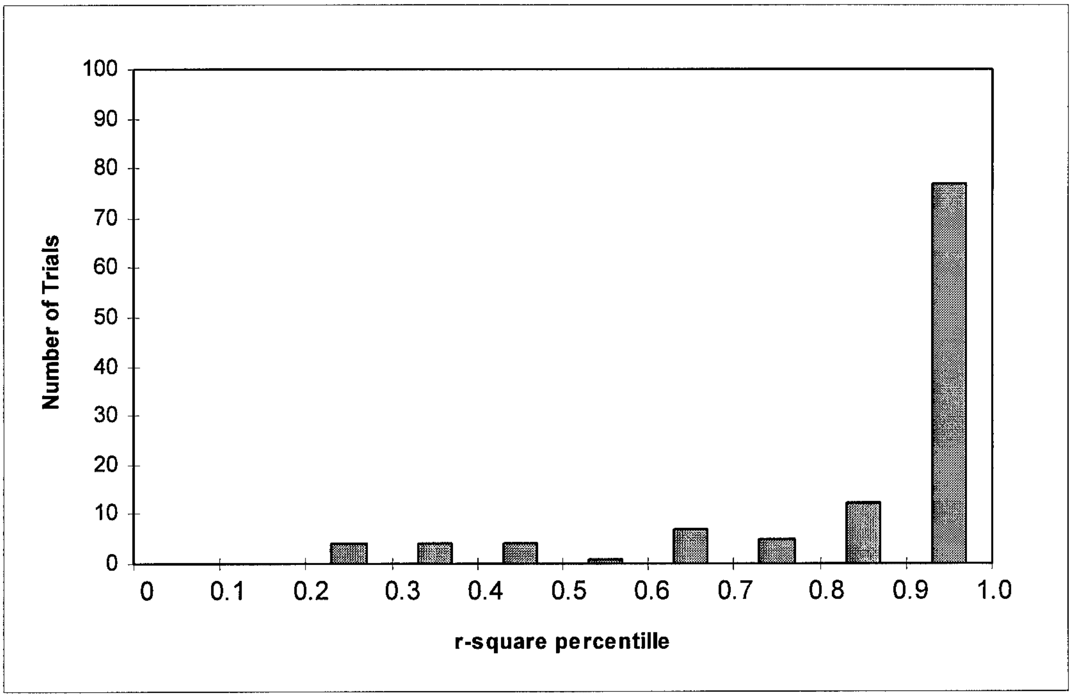

Figure 2.3. Distribution of the r^2s for the performance of Model 3, applied to female subjects (N=16) in the Pelvic Support Structure.

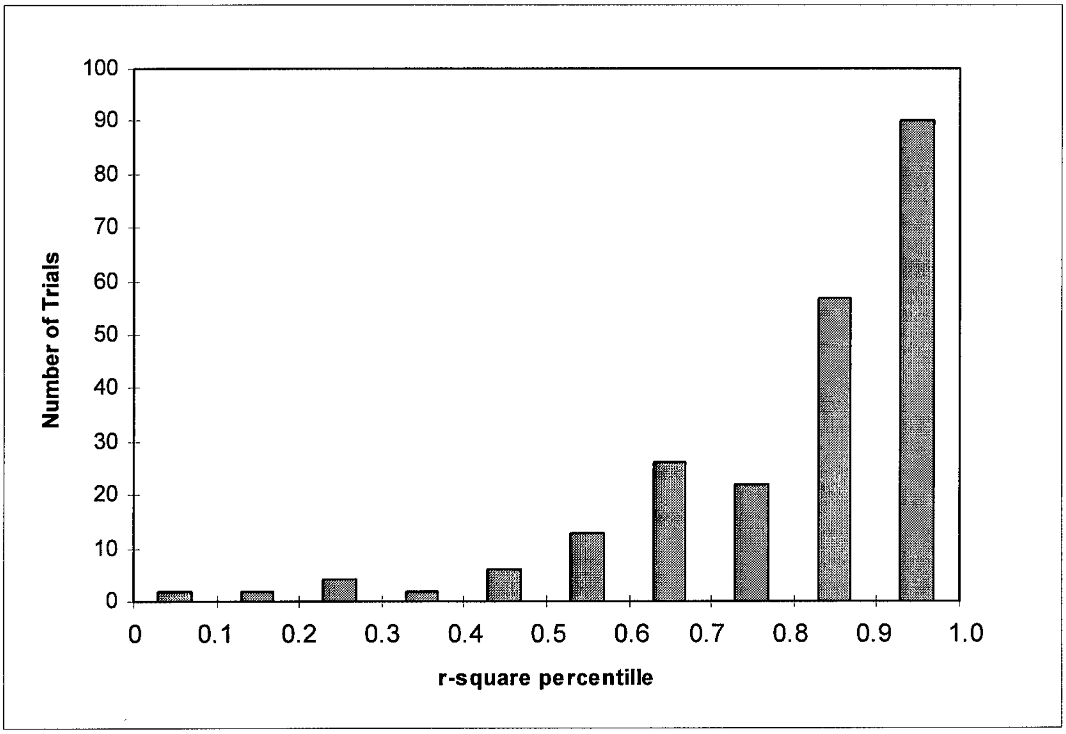

Figure 2.4. Distribution of the r^2s for the performance of Model 3, when the length-strength and force-velocity modulation factors derived from trials in the PSS were applied to the lifting trials performed in the Free Dynamic conditions (N=28).

Modulation Factors

The final muscle length-strength and force-velocity modulation factors which were used to develop the model performance results in Table 2.8 are shown below, where equation 2.5 is the female length-strength modulation factor, and equation 2.6 is the female force-velocity modulation factor:

$$f(\text{Length}_j) = 5.116 - 13.615\times\text{Length}_j + 11.705\times\text{Length}_j^2 - 2.195\times\text{Length}_j^3 \quad (Eq.\ 2.5)$$

$$f(\text{Vel}_j) = 1.036 - 0.0725\times\text{Velocity}_j \quad (Eq.\ 2.6).$$

For comparison purposes, the male muscle length-strength and force-velocity modulation factors determined by Granata and Marras (1995) are shown below in Equations 2.7 and 2.8, respectively:

$f(\text{Length}_j) = -3.25 + 10.2\times\text{Length}_j - 10.4\times\text{Length}_j^2 + 4.59\times\text{Length}_j^3$ *(Eq. 2.7)*

$f(\text{Vel}_j) = 0.4e^{(V/-0.38)} + 0.76$ *(Eq. 2.8)*.

The regression line of the female length-strength modulation factor (equation 2.5) is contrasted against the raw data as a function of the sagittal moment ratio ($M_{x\text{-meas}}$ divided by $M_{x\text{-pred}}$ as shown in Figure 2.5, with the male length-strength modulation factor from equation 2.7 (Granata and Marras, 1995) plotted against the female length-strength modulation factor in Figure 2.6 for comparison purposes. The general shape of the two curves are very similar, with a small offset where the males moment ratio is slightly higher for every point along the muscle length axis. The female force-velocity raw data is shown plotted against the modulation factor regression equation (equation 2.6) for the females in Figure 2.7, with the male force-velocity modulation factor (equation 2.8) plotted against the female force-velocity modulation factor (equation 2.6) in Figure 2.8. The two curves in Figure 2.8 are somewhat different, with the female force-velocity modulation factor remaining almost linear with a slight negative slope, with the males exhibiting a greater moment ratio near the slower velocities, and smaller moment ratios as the velocity of contraction increases.

Table 2.7. Model results as a function of each of the five models, with different inputs for the cross-sectional areas, length-strength (L-S) and force-velocity (F-V) modulation factors, vector locations, and lifting trials used. The modulation factors determined from the trials in the ***Pelvic Support Structure*** were then used to assess the model using the ***Free Dynamic*** lifting trials, respectively for each of the Models (e.g., 1,2,3,4, and 5).

Model	Muscle Areas	L-S and F-V Factors	Vector Locations	Lifting Trials	Statistic	Pelvic Support Structure (N=12)			Free Dynamic (N=28)		
						Gain	r^2	AAE	Gain	r^2	AAE
1	Male	Male	Male	All	Mean	119.0	0.64	4.2	289.5	0.48	13.7
					s.d.	74.2	0.39	4.3	365.0	0.38	15.6
					Median	106.9	0.90	3.0	193.6	0.48	7.5
				Dynamic	Mean	86.0	0.91	5.8	159.4	0.81	22.2
					s.d.	36.9	0.11	4.8	69.6	0.19	13.9
					Median	83.3	0.95	4.5	148.5	0.88	19.1
2	Female	Male	Male	All	Mean	56.4	0.44	5.8	120.4	0.37	16.2
					s.d.	33.5	0.38	5.1	95.8	0.32	17.8
					Median	51.8	0.41	3.5	98.8	0.27	9.1
				Dynamic	Mean	49.3	0.68	8.6	82.6	0.57	26.8
					s.d.	30.0	0.32	5.1	33.3	0.29	15.2
					Median	45.9	0.82	8.5	84.7	0.64	24.0
3	Female	Female	Male	All	Mean	46.5	0.65	4.0	109.1	0.49	13.1
					s.d.	29.2	0.39	3.7	126.6	0.38	14.7
					Median	41.1	0.92	2.9	74.9	0.52	7.6
				Dynamic	Mean	32.9	0.93	5.4	60.8	0.81	20.5
					s.d.	14.2	0.07	4.0	26.5	0.18	12.3
					Median	31.9	0.95	4.3	57.2	0.87	18.4
4	Female	Female	Hybrid	All	Mean	74.1	0.50	7.4	176.0	0.40	16.2
					s.d.	119.6	0.36	9.8	372.8	0.35	35.0
					Median	49.0	0.58	4.8	96.6	0.32	7.9
				Dynamic	Mean	42.7	0.67	8.8	75.9	0.64	15.7
					s.d.	21.0	0.29	6.2	31.6	0.29	15.4
					Median	42.9	0.78	6.9	74.5	0.74	12.5
5	Female	Female	Female	All	Mean	71.2	0.39	9.7	151.1	0.26	10.1
					s.d.	95.0	0.33	7.5	262.0	0.25	11.4
					Median	43.8	0.29	9.9	87.1	0.18	7.0
				Dynamic	Mean	38.7	0.47	15.2	68.2	0.38	14.4
					s.d.	15.5	0.30	4.6	28.1	0.27	7.5
					Median	38.8	0.54	15.1	62.7	0.36	13.5

Table 2.8. Model performance results from Model 3 (see Table 2.2) with female cross-sectional areas, female length-strength and force-velocity modulation factors, and male muscle vector locations. This model includes four additional subjects for the pelvic support structure (N=16), with the updated modulation factors applied to the free dynamic lifting trials (N=28).

Lifting Trials	Statistic	Pelvic Support Structure			Free Dynamic		
		Gain	r^2	AAE	Gain	r^2	AAE
All Trials	Mean	45.5	0.65	4.3	116.7	0.49	12.8
	s.d.	27.5	0.38	3.7	164.2	0.38	14.3
	Median	37.0	0.90	3.1	78.1	0.51	7.6
Dynamic Only	Mean	32.3	0.91	5.8	62.3	0.81	19.9
	s.d.	12.6	0.13	3.7	27.2	0.19	11.9
	Median	30.7	0.94	4.5	57.9	0.88	17.7

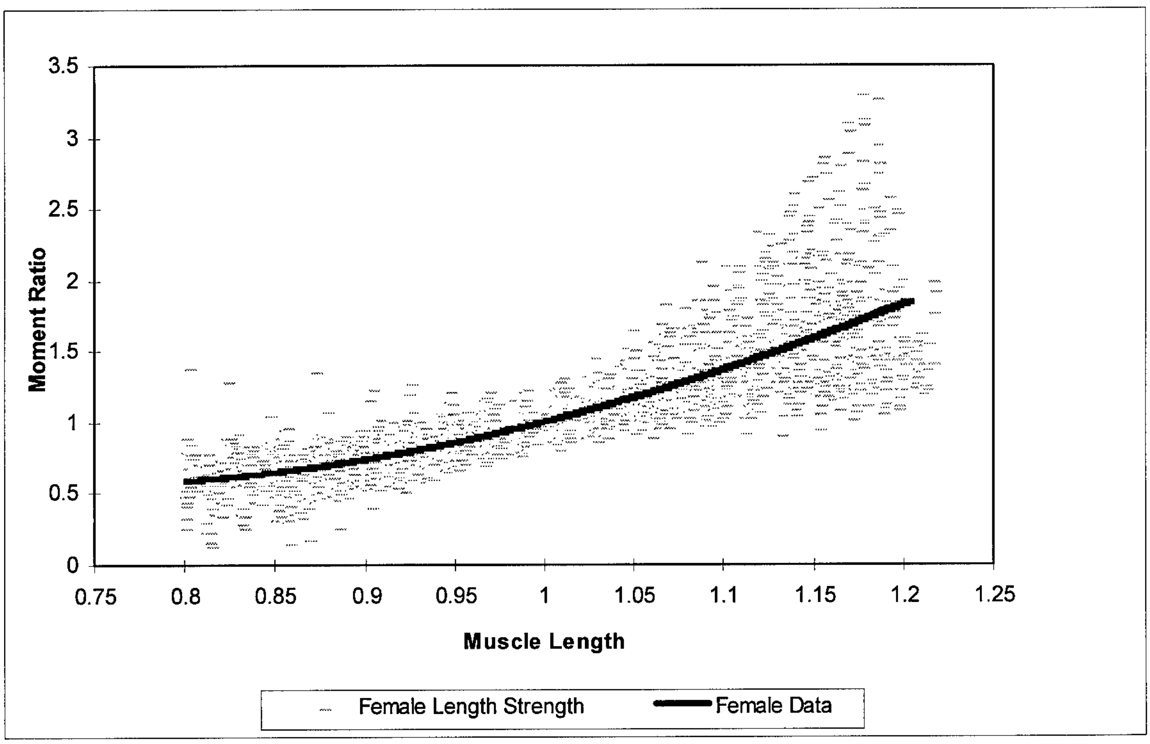

Figure 2.5 Female length-strength modulation factor data and regression line, as a function of relative muscle length and predicted to measured moment ratio.

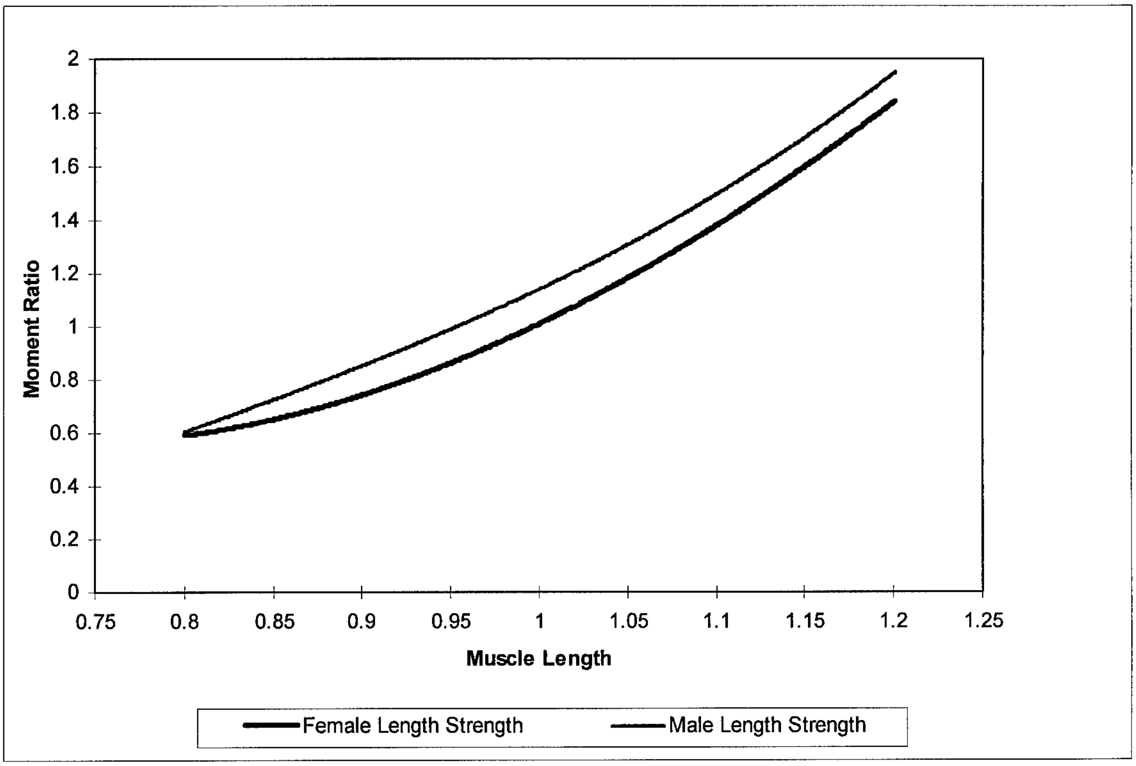

Figure 2.6 Female length-strength versus male length-strength modulation factor comparison.

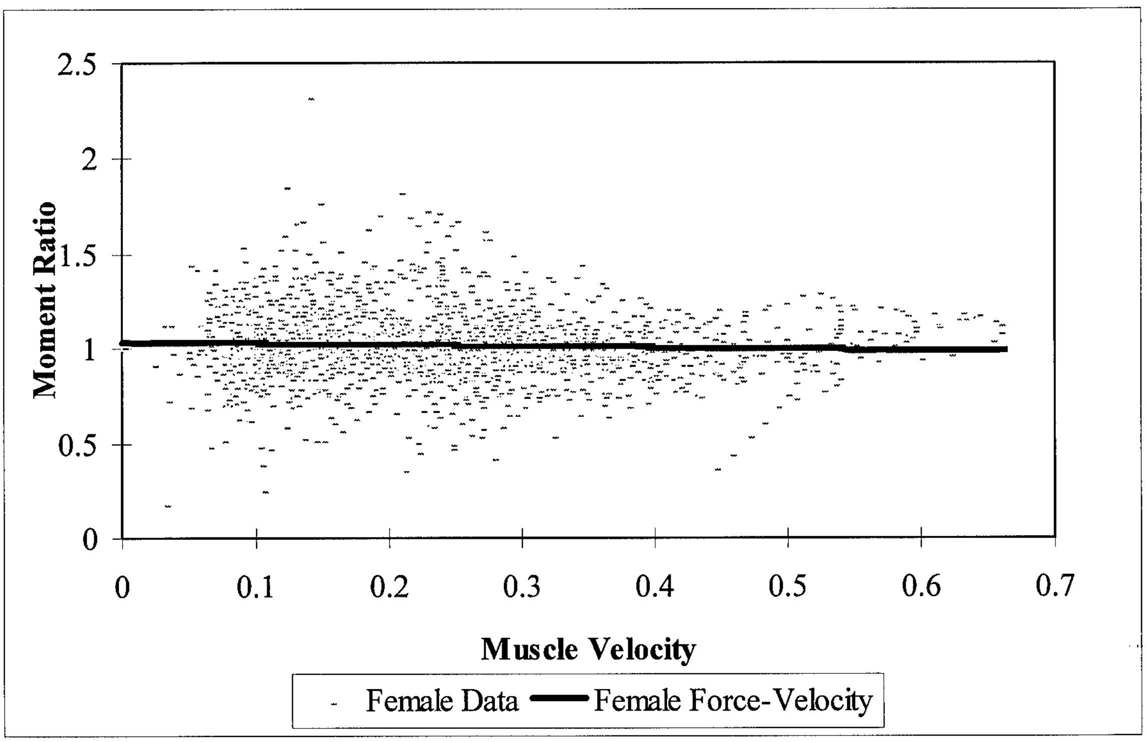

Figure 2.7. Female force-velocity modulation factor data and regression line, as a function of muscle velocity and predicted to measured moment ratio.

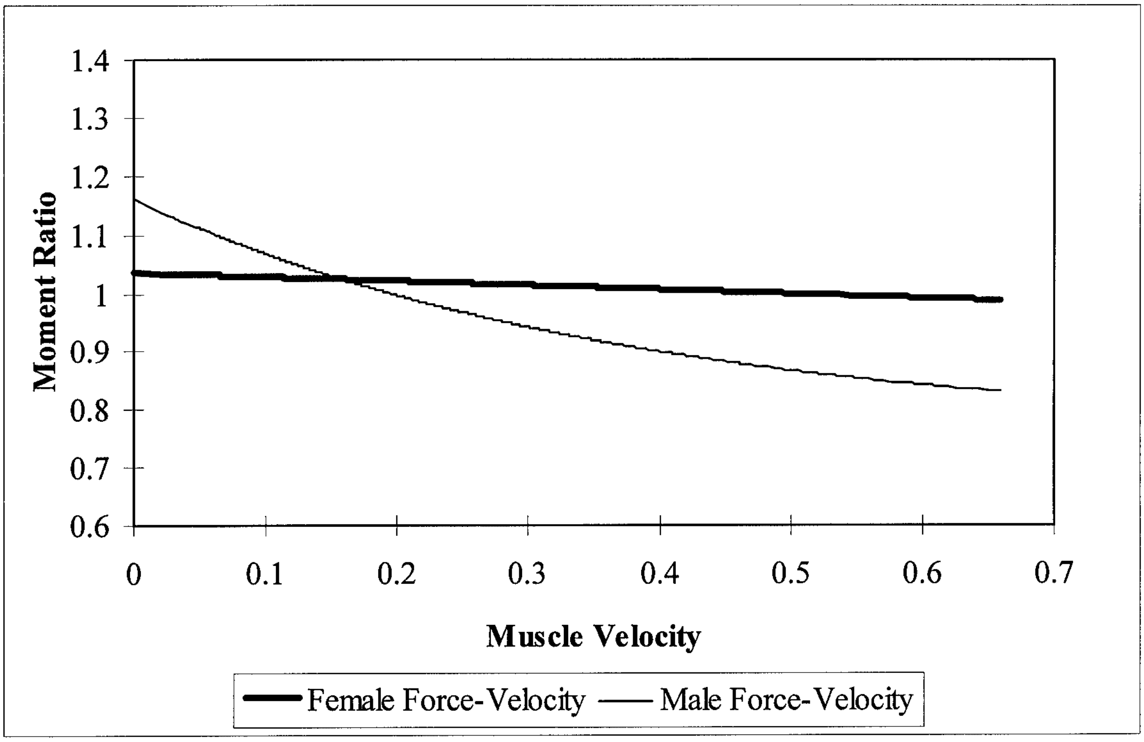

Figure 2.8 Female force-velocity versus male force-velocity modulation factor comparison.

Discussion

The results described in this research on female muscle length-strength and force-velocity relationships have not previously been reported by other researchers. Thus, there are no other female datasets available for comparison purposes. The length-strength modulation factor for the females (Figure 2.6) appears to follow very closely the shape of the length-strength relationship found by other researchers (Marras and Sommerich, 1991b; Granata and Marras 1993), with the females exhibiting a smaller measured to predicted moment ratio at every muscle length. However, this study did result in different shapes for the force-velocity modulation factors, especially at the extremes of the velocities (Figure 2.8). These differences may indicate that males and females muscles respond differently during lifting activities. The development of these modulation factors for the females followed previously used methods, including restricting the data to a sagittal flexion range to ensure that the active loading structures as well as limiting the lifting trials to sagittally symmetric exertions, and modeling the erector spinae muscle only. The decision to model only the erector spinae muscle appears valid, as the descriptive results for the normalized muscle activity revealed that this muscle group was by far the most active at all velocities and weights examined.

The systematic approach to developing the length-strength and force-velocity modulation factors allowed a systematic evaluation of the contribution of different inputs into the biomechanical model, through the model performance parameters of r^2's, muscle gains, and the average absolute error between the predicted and measured moments. The improvement of the biomechanical model performance over the male only model (Model 1) was accentuated when utilizing the female specific cross-sectional area equations as well as the female length-strength and force-velocity modulation factors, as the average and median r^2 were 0.91 and 0.94, respectively, with valid average muscle gains and low errors between the predicted and measured sagittal moment. Thus, the findings from Part 1, and the differences shown in the modulation factors and model inputs as a function of gender indicate that indeed a female specific biomechanical model is warranted to permit accurate assessment of spinal loading during material handling tasks. This also indicates that there is promise to successfully achieve the objectives for Part 3 of this research.

Limitations

A few limitations do exist at this point in the research. First, the lifting exertions which were modeled consisted of only sagittally symmetric exertions, and the relationship between spinal loading and muscle activity may be different in asymmetric conditions. These relationships, however, will be investigated in Part 3 of this, during a validation phase.

Decreases in the model performance parameters occurred when applying the length-strength and force velocity modulation factors to the lifting trials performed in the Free Dynamic mode. Specifically, the mean r^2 decreased from 0.91 to 0.81, and the mean muscle gains almost doubled, although they were still within the physiologically valid range. This may be a function of allowing the pelvis and hips to rotate and further changing the length-strength and force-velocity relationships in the Free Dynamic mode, and thus changing the mechanics of the lifting and resulting EMG values. This very subject is currently being investigated in our lab, to determine the influence of allowing the hips and pelvis to rotate during lifting activities. Finally, the female equivalent of the muscle origin and insertion locations for the current male biomechanical model was not used to develop the female length-strength and force-velocity modulation factors, as these have yet to be developed. Given that we now have male data representing the muscle vectors, we now have the ability to check previously reported vector coefficients with the database from male subjects collected in Part 1. Thus, the relationships between the published muscle vector locations and the database of the males will be explored first, then extended to the females database.

Problems Encountered During this Reporting Period

As discussed above, the analyses from the Free-Dynamic lifting trials did not result in acceptable model performances, with low r^2's and high gain values. Thus, it was hypothesized that the subjects were performing different motions with their hips and pelvis's, resulting in highly variable results. Therefore, to remove the potential confounding effect of the rotation of the pelvis and hips, additional subjects were collected in a device which restricted movement to the trunk only, and not the pelvis. The modulation factors determined from this new dataset are very promising, even when applied to the data to the Free-Dynamic lifting exertions.

Additional subjects are currently being recruited and run through the experimental protocol in the Pelvic Support Structure, as well as to complete the agreed upon sample size for the Free-Dynamic lifting protocol. It is felt that the collection of the additional subjects will solidify the female length-strength and force-velocity modulation factors, and will produce acceptable results when applied to the free-dynamic exertions.

Conclusions

The derived female muscle length-strength and force-velocity relationships, when applied to the EMG-assisted biomechanical models resulted in very good model performance parameters, including the r^2's between the predicted and measured moment, physiologically valid muscle gain values, and small magnitudes of error between the predicted and measured moment. The original procedure used to collect the data, however, had to be adjusted to reduce the variability in the length-strength and force-velocity modulations resulting from allowing the hips and pelvis to rotate during the lifting exertions. Thus, the lifting trials performed with the pelvis constrained resulted in very good model performance, and when applied to the trials collected during the free dynamic conditions resulted in somewhat lower, but still acceptable model performance parameters. It is expected that with the collection of the final subjects with the constrained pelvis, and applying the muscle modulation factors to the free dynamic conditions, that appropriate adjustments can be made to the free dynamic conditions to account for the variability due to allowing the hips and pelvis to rotate.

The use of the female muscle-cross-sectional areas derived in Part 1 resulted in increases in performance over the male only biomechanical. This data, combined with the length-strength and force-velocity modulation factors for the females results in a promising dynamic EMG-assisted biomechanical model, when positions us well for the analysis of asymmetric lifting exertions in Part 3 of this research.

Part 3: Implementation and Validation of the EMG-assisted Model for Female Subjects.

Introduction

Much of the manual material handling activities (e.g., lifting) are not performed in a sagittally symmetric posture, but must be performed with trunk asymmetry involved. Thus, motions such as twisting or lateral side bending most likely is involved to some degree in most lifting activities. The biomechanical model parameters developed in Part 2 were developed under sagittally symmetric lifting exertions. Thus, the goal of Part 3 is to use the parameters developed for the females and apply to asymmetric lifting exertions, and adjust the model such that the model performs well under sagittally symmetric exertions as well as asymmetric exertions.

Background and Objectives

The Biodynamics Laboratory EMG-assisted model, which predicts the three-dimensional spinal loading experienced by subjects during manual handling tasks currently has only been validated for males. The results of Part 1 and Part 2 as reported in this progress report indicate that females differ from males with respect to muscle anthropometry (e.g., muscle cross-sectional areas as a function of external anthropometry, and muscle lines of action), as well as muscle length-strength and force-velocity relationships. These differences undoubtedly will have an affect on the accuracy of the spinal loads predicted by the EMG-assisted biomechanical model. Thus, the objectives of Part 3 include 1) utilizing the model parameters derived from Part 1 and Part 2 and implementing these into the current form of the EMG-assisted biomechanical model, and 2) validation of the female-specific EMG-assisted biomechanical model for sagittally-symmetric and asymmetric lifting exertions.

Administrative Note

Data collection for Part 3 has begun, and currently, data has been collected from seven female subjects and four male subjects. The accepted research proposal calls for 40 military age female subjects and 20 male subjects to be used for comparison purposes. Thus, data collection for this part is on schedule, with data collection expected to be completed by summer of 1998. Also in the accepted research proposal, weight conditions of 15, 50 and 80 lbs. were to be used for female as well as male subjects. However, we have yet been able to find a female capable of lifting 80 lbs. up to a height of 102 cm above the floor. Thus, the experimental design has been modified to still allow three weight levels, including 15, 30, and 50 lbs. It is felt that this weight is more realistic for the capabilities of the female population, especially for the number of repetitions required by our experimental design for this study.

Methods

Experimental Design

The subjects will perform free-standing lifts representative of select military material handling tasks. Weights of 15, 30, and 50 lbs. will be lifted from starting positions near ankle level and knee level to destinations at waist height and 102 cm elevation. These lifting tasks will include starting and destination positions at the subject's side (asymmetric lifts) as well as directly in front of them (sagittally symmetric). Each subject will perform each lifting combination twice.

The independent variables are intended to simulate a range of realistic military material handling conditions as specified in the MOS Physical Task list (11), and to assess model sensitivity and applicability for female subjects. The independent variables include weight of lift (15, 30, and 50 lbs.), starting height (ankle and knee), vertical destination height (waist and 102 cm above the floor), degree of asymmetry (0 and 60 degrees), and gender. This blocked (gender) repeated measures design will result in 48 experimental trials per subject, thus permitting sensitivity analysis of those material handling factors that might influence model performance. The presentation order of the experimental conditions will be counterbalanced and subjects will be permitted at least two minute rest (54) or as much time as needed between trials to minimize the risk of fatigue and carryover effects on the results.

The dependent variables will consist of several model measures of performance. For a model to be considered robust and accurate it must, 1) accurately represent the changes in trunk and spine loading over time and, 2) accurately estimate the magnitude of the trunk loading during the lift. The squared correlation (r2) between the measured and predicted trunk moments will serve as an indicator of the model ability to accurately assess the changes in trunk loading. Measured versus predicted magnitudes of the load imposed upon the trunk will be assessed by comparing the average moments applied by the trunk during lifting trials as well as mean square error (MSE) measures of dynamic performance. In addition, predicted muscle gains can be used as a measure of the physiologic validity.

Subjects

The subjects in this Part will consist of 20 males and 40 females, all of generally observed military age. Male subjects shall be recruited to permit comparison and calibration of model performance and results with female subjects. Subject anthropometric characteristics will be matched so that subjects between the 5th and 95th percentiles of military height and weight are represented.

Equipment

The equipment used in this part has been previously described in Part 2. Specifically, subjects will stand on a force plate (not moving their feet), and will perform lifts from ankle and knee heights to destinations of waist height and 102 cm above the floor. The forces and moments measured by the force plate will be rotated and translated to the estimated position of the L_5/S_1 through the use of a sacral location orientation monitor and a pelvic orientation monitor (Fathallah et al., 1997). The subjects trunk three-dimensional position, velocity, and acceleration will be measured by an LMM (Marras et al, 1992), and trunk muscle activity will be measured through electromyography, placed over right and left sides of five trunk muscle groups (Mirka and Marras, 1993).

Data Analyses

Two forms of analyses will be performed. First, time-dependent predicted trunk moments will be compared with the measured trunk moment via an r^2 statistic. Second, the magnitude of the model prediction will be assessed by comparing the average predicted and measured moments and examining the MSE statistic. An r^2 value of 0.80 or above over all trials will indicate that the model is working well. A t-test will be used to test the significance of magnitude of difference between the predicted and measured trunk moments overall. A difference of no more than 10% will be considered acceptable. An MSE representing a sum of variations no greater than 20% of the measured moment will be accepted. Analysis of variance (ANOVA) procedures will be used to test the significance of these three measures as a function of the independent variables and their two-way interactions. Significant differences will indicate different levels of model performance between the conditions and can be used as a model sensitivity measure. Tukey post-hoc procedures will be used to understand the nature of these differences. This procedure will allow us to pinpoint the portions of the model that require further development. Finally, to assure physiological feasibility, predicted muscle gains must fall between 30 and 90 $N{\cdot}cm^{-2}$ (McGill et al, 1988; Reid and Costigan, 1987; Weis-Fogh and Alexander, 1977).

Conclusions

Part 3 of this research, which consists of validating the chosen female model parameters determined from Part 1 and Part 2, is currently in the initial stages of data collection. Seven of 40 female subjects have been collected, and 3 of 20 males have been collected for comparison purposes. Thus, the data collection is underway, and is expected to be completed and analyzed within the agreed upon time frame.

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DEPARTMENT OF THE ARMY
US ARMY MEDICAL RESEARCH AND MATERIEL COMMAND
504 SCOTT STREET
FORT DETRICK, MARYLAND 21702-5012

REPLY TO
ATTENTION OF:

MCMR-RMI-S (70-1y)

1 JUN 2001

MEMORANDUM FOR Administrator, Defense Technical Information Center (DTIC-OCA), 8725 John J. Kingman Road, Fort Belvoir, VA 22060-6218

SUBJECT: Request Change in Distribution Statement

1. The U.S. Army Medical Research and Materiel Command has reexamined the need for the limitation assigned to technical reports. Request the limited distribution statement for reports on the enclosed list be changed to "Approved for public release; distribution unlimited." These reports should be released to the National Technical Information Service.

2. Point of contact for this request is Ms. Judy Pawlus at DSN 343-7322 or by e-mail at judy.pawlus@det.amedd.army.mil.

FOR THE COMMANDER:

Encl

PHYLLIS M. RINEHART
Deputy Chief of Staff for
Information Management

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